Regional Environmental Change (2024) 24:51
https://doi.org/10.1007/s10113-024-02197-5

ORIGINAL ARTICLE

Changes in grassland cover in Europe from 1990 to 2018: trajectories and spatial patterns

Robert Pazúr[1,2] · Jozef Nováček[1] · Matthias Bürgi[2] · Monika Kopecká[1] · Juraj Lieskovský[3] · Zuzana Pazúrová[1] · Ján Feranec[1]

Received: 3 August 2023 / Accepted: 3 February 2024

Abstract

Grasslands are one of the most widespread terrestrial biomes. In Europe, the majority of grasslands depends on human management, and as a result, grassland areas are facing different dynamics and transitions to other land cover types. This study identifies the trajectories in grassland cover in Europe from 1990 to 2018. Using a 1 km × 1 km grid spanning most European countries, we identified increasing, decreasing and mixed development trajectories of grassland cover. For each development trajectory, we selected four representative hotspots and identified the land cover and its changes over different periods. Our results reveal that the decreasing development trajectory occurred on 35% of the aggregated grids with hotspots in Eastern Europe, the Mediterranean region and the UK. The increasing development trajectory occurred on 20% of the aggregated grids, centred in Central Europe, and the mixed development trajectory occurred on 3% of the aggregated grids. Within the selected hotspots, the development trajectories were linked to transitions among agricultural land cover classes or to transitions with shrubs and urban areas. The development trajectories also indicated strong country-specific differences, suggesting a strong impact of national policies. The generated outcomes of this study can be used to support decision-making on future pathways for grassland habitats on a European scale.

Keywords CORINE land cover · EU agriculture · Cropland · National policies · Agricultural land use change

Introduction

Grasslands, along with forests and shrublands, cover most of the Earth's terrestrial surface (Buchhorn et al. 2020). Grasslands are mostly disturbance-dependent ecosystems, meaning that they often require human management, such as mowing or grazing, to maintain their diversity and productivity (Blüthgen et al. 2012; Schils et al. 2022). Thus, the changes in grasslands area extent (e.g. afforestation), as well as the changes in grassland species composition, are strongly related to human activities.

Grasslands also provide a variety of ecosystem services (Isselstein and Kayser 2014; Bengtsson et al. 2019; Zhao et al. 2020) including provisional (e.g. food supply, freshwater supply, fuel supply, regulating (e.g. climate regulation, carbon sequestration, soil erosion control, water regulation) and cultural ecosystem services (e.g. aesthetic appreciation and cultural heritage).

Historically, grassland dynamics in Europe was primarily linked to its interchange with croplands (Fuchs et al. 2015). Such interchange between both the agricultural land use systems likely resulted either from the short-term crop rotation practices, or from the long-term land use changes, such as abandonment and recultivation. In recent decades, however, urbanisation, afforestation and the abandonment of marginal areas have been the primary drivers of declining grassland extent in Europe (Huyghe et al. 2014).

The persistence and changes in the grassland cover in Europe are strongly affected by the national policies (Prishchepov et al. 2017; Commission et al. 2020)

Communicated by Wolfgang Cramer

✉ Robert Pazúr
robert.pazur@wsl.ch

1 Institute of Geography, Slovak Academy of Sciences, Bratislava, Slovakia

2 Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

3 Institute of Landscape Ecology, Slovak Academy of Sciences, Bratislava, Slovakia

(Prishchepov et al. 2017). For instance, the widespread abandonment of the agricultural land in Eastern Europe following the collapse of socialism (Müller et al. 2009; Munteanu et al. 2014) and later countered by recultivation triggered by Common Agricultural Policies (CAP) in the EU member countries (Pazúr et al. 2020). Grassland development is also further by the changes in the livestock population and feeding habitats, the implementation of milk quotas, a shift between hay and silage making and adoption of weed control and irrigation measures (Peeters 2012).

The importance of grassland ecosystems in Europe is underlined by various initiatives and projects related to monitoring of grassland biodiversity and management (Kolecka et al. 2018; Griffiths et al. 2019). Three landcover mapping initiatives, supported mostly by the European Union's Earth observation programme (Copernicus Programme 2021), provide multitemporal spatial information on grassland distribution. The Land Use/Cover Area Survey (LUCAS) is a point-based mapping initiative, that combines the visual interpretation of aerial images with massive in situ data collecting. The data from LUCAS are currently available for 2006, 2012 and 2018 (Eurostat 2015). The LUCAS datasets provide in situ information with high precision and reliability, including landscape photos and different environmental parameters (Weigand et al. 2020; d' Andrimont et al. 2020). Another mapping initiative, Copernicus high-resolution layer (HRLs), provides grassland maps based on radar and optical data in 20-m and 10-m resolution for 2015 and 2018, respectively (Copernicus Land Monitoring Service 2020). Long-term changes in the European landcover, however, are only covered with the CORINE land cover dataset (Feranec et al. 2010; Bielecka and Jenerowicz 2019), which provides land cover maps for 1990, 2000, 2006, 2012 and 2018. A limitation of CORINE land cover dataset is its insensitivity to small-scale changes due to the minimum mapping units (25 ha for areal phenomena, a 100 m for linear phenomena and 5 ha for changes of land cover class) and areas of change assessed (Diaz-Pacheco and Gutiérrez 2014; Pflugmacher et al. 2019).

Besides these mapping initiatives supported by the European agencies, grassland management intensity at the EU level was mapped using MODIS NDVI time series from 2000 to 2012 (Estel et al. 2018). On a national scale, the frequency and timing of grassland mowing events were mapped in Germany with the use of Landsat and Sentinel-2 satellites (Griffiths et al. 2019). A similar evaluation was performed at the district scale in Switzerland (Kolecka et al. 2018). Using Landsat satellite imagery for mapping abandonment and recultivation trends on grassland areas was the focus of various research projects related to the agricultural land cover change in Central and Eastern Europe (Alcantara et al. 2012; Griffiths et al. 2013). However, an encompassing assessment of long-term dynamics of grasslands across the whole Europe is so far missing. Such information may bring important insights into the dynamics of the grassland ecosystems, reveal regional differences and indicate potential factors influencing the dynamics of the world's biggest biome.

This paper aimed to map the grassland change trajectories and their spatial patterns at the regional and national scale in Europe. Starting in 1990, we covered most of the European countries and their grassland development within the periods of 1990–2000, 2000–2006, 2006–2012 and 2012–2018.

Specifically, we asked the following research questions:

a) What were the grassland cover development trajectories in Europe since 1990?
b) What was the spatial distribution of different trends of grassland dynamics in Europe?

Data and methods

We utilised the CORINE land cover datasets to assess the dynamics of grasslands in Europe considering the land cover changes in 1990, 2000, 2006, 2012 and 2018. CORINE land cover contains 44 different land cover classes at the third hierarchical level of the nomenclature. The hierarchical structure of the nomenclature divides the five main land cover classes at the first hierarchical level: artificial surfaces, agricultural areas, forest and seminatural areas, wetlands and water bodies. The classification system is well established in European-based studies and may link to different classification systems, such as FAO, through its metadata (O' Brien C.D. et al. 2021). The minimum polygon mapping area is 25 ha and the minimum land cover change mapping area is 5 ha (Heymann 1994; Bossard et al. 2000; Feranec et al. 2016).

Our analysis is based on two land cover classes related to grasslands:

– pastures and meadows (CORINE land cover class 231) referring to grassland areas used for agricultural purposes such as mowing and livestock grazing (it includes permanent and temporal grassland and does not include the grassland of rotation system) (Bossard et al. 2000);
– natural grasslands (CORINE land cover class 321) including natural grasslands such as alpine grasslands, arid limestone areas or steppes (Bossard et al. 2000);

Table 1 Illustration of the possible development trajectories of the grassland area. The rows refer to the reference period of 1990, while the columns stand for any period different from 1990 (2000, 2006, 2012, 2018). The arrow represents either the (↑) increasing, (↓) decreasing trajectory or its combination (↑↓) is the mixed trend. The (=) sign refers to the stability of the grassland area in the particular grid and period of change

	Land cover 1990+				
		1990+	1990+	1990+	1990+
Reference land cover	1990	=	=	=	=
	1990	↑↓	=	=	=
	1990	↑↓	↑↓	=	=
	1990	↑↓	↑↓	↑↓	=
	1990	↑↓	↑↓	↑↓	↑↓

Assessment of the grassland dynamics

We assessed the dynamics and the development trajectories of grasslands using 1 km × 1 km square grid spanning the entire European terrestrial area. For further analysis, we selected all grid cells containing more than 0.05% (0.5 ha) of grassland areas. The trajectory of changes in these grid cells was compared to the reference land cover dataset for 1990 dataset. Furthermore, we classified the grid cells based on their development trajectories using the following criteria:

- increasing development trajectory (A) - areas of grasslands in 2000, 2006, 2012 and 2018 are larger than in the reference year of 1990 (see Table 1);
- decreasing development trajectory (B) - areas of grasslands in 2000, 2006, 2012 and 2018 are smaller than in the reference year 1990
- mixed development trajectory (C) - areas of grasslands in all years of observation have mixed extent within the squares (a combination of increasing, decreasing and equal extent as compared with the reference year of 1990).

To further investigate the specific land cover changes that contributed to the observed development trajectories, we evaluated the transition matrix between different land cover classes (CORINE land cover 2nd classification level). For this purpose, we selected 12 hotspot areas of 25 km × 25 km, four for each analysed grassland development trajectory (increasing, decreasing, mixed). Hotspot areas were identified using a moving window approach quantifying the presence of the development trajectory within a 25 × 25 km^2 window weighted by the proportion of grasslands within that specific window. For each hotspot area, only land cover changes that were directly related to grasslands or accounted for more than 25% of the selected square area were considered relevant to describe the trends in the selected landscape.

Results

Grassland development trajectories in Europe

In total, 31% of all 1 km × 1 km grids across Europe contained the defined minimum grassland coverage in 1990. Most of these grids were stable from 1990 to 2018 (41%), followed by decreasing (35%), increasing (20%) and mixed (3%) trajectories of grassland development (Table 2). Most of the stable grasslands were concentrated in the northern part of Europe (Fig. 1), in the countries with various proportion of grassland areas (Norway, Sweden, Belgium, Denmark) (Fig. 2). The appearance of both the increasing and decreasing development trajectory in a single country was found in Ireland, in the region of Central Europe (Austria, Germany), Eastern Europe (Romania) as well as in the Mediterranean region (Northern Macedonia, Albania) (please refer to the supplementary material (Appendix A)). Decreasing trajectories showed hotspots in Mediterranean Europe, particularly in southern Italy and western Spain. Decreasing grassland development trajectories were also observed in the Baltic countries (Lithuania, Latvia, Estonia), as well as in Slovakia, Ukraine and western England. Increasing grassland development trajectory was found on more than 35% of the analysed squares in the Czech Republic, especially in its border regions. Hotspots of grassland increase were also found in the central parts of Germany, Austria and western England.

Representative areas of different trajectories of grassland change

The landscapes of selected 25 km^2 areas were mostly composed of multiple patches of agricultural areas and forests (Fig. 3). The dynamics between the land cover classes (ranging between 8 and 49 % of the total area) were mostly linked to the interchange between arable land, grasslands and heterogenous agricultural areas. The increase in grassland extent

Table 2 Summary of trajectories of grassland change in the period 1990–2018

Trend	Number of 1 km × 1 km^2	%	Difference between 2018 and 1990 (km^2)
Increasing	381,744	20	88,486
Decreasing	670,316	35	46,286
Mixed	61,806	3	2067
Stable	782,721	41	92,694
Total*	1,896,587	100	

*Sum of the grid squares where the grasslands area reached more than 0.05% (0.5 ha)

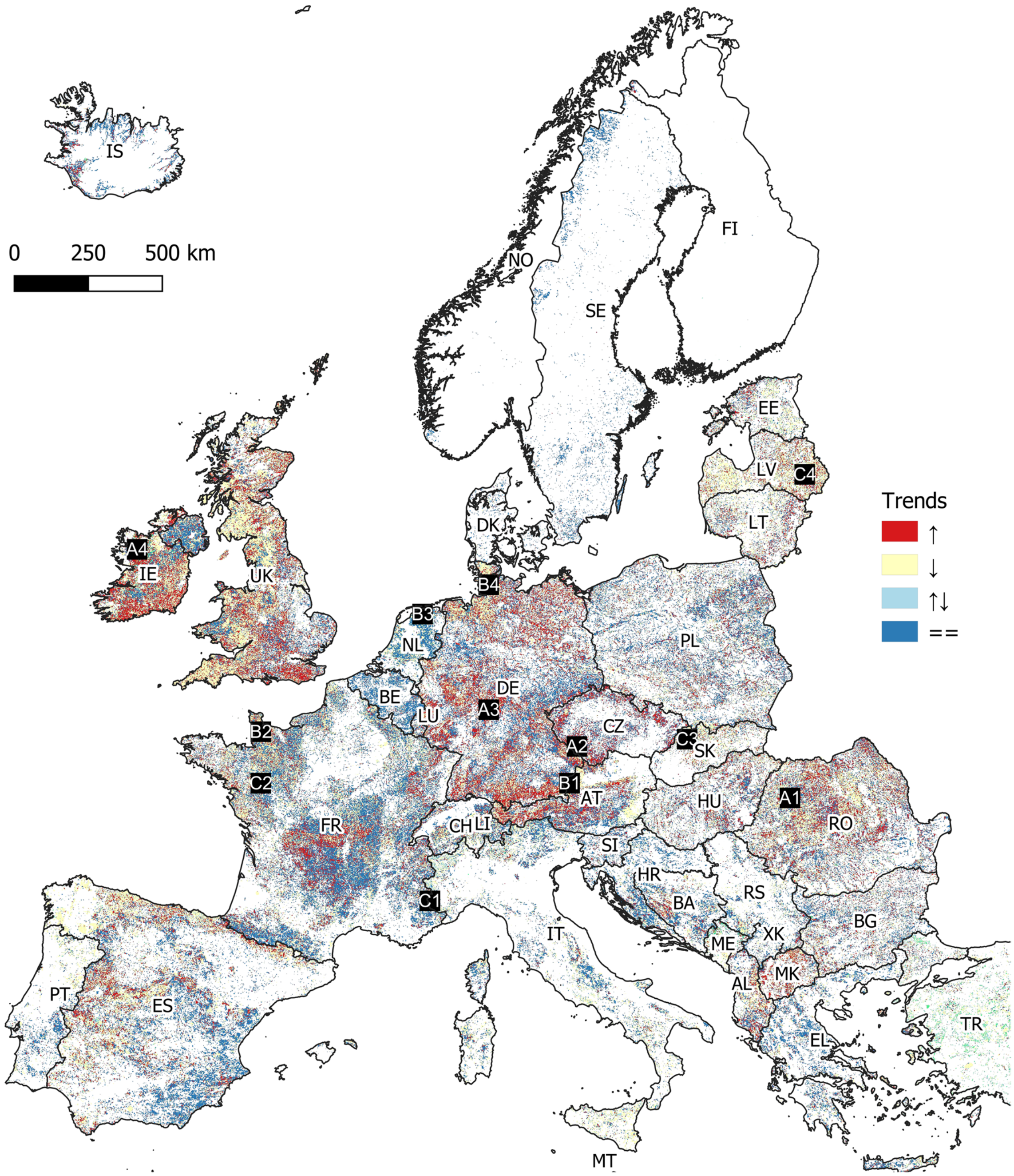

Fig. 1 Grassland development trajectories in Europe in the period 1990-2018. (increasing ↑; decreasing ↓; mixed ↑↓; == stable). Rectangles illustrate the allocation of the selected representative areas of: increasing (**A**), decreasing (**B**), mixed (**C**) grassland development trajectories. The two-letter country codes are based on the ISO 3166 standard for country identification

was observed mostly as a transition from arable land and heterogenous agricultural areas (Fig. 4). The decrease of grassland was related to the opposite transition to arable land and heterogenous agricultural areas but also to the transformation to urban areas. Mixed development trajectories within their selected hotspots were related to the interchange between cropland, grassland, heterogeneous agricultural areas, shrubs and open spaces with no vegetation.

Discussion

Identified trends in grassland change across Europe

Using the land cover datasets, we evaluated different grassland development trajectories across Europe during the period of 1990–2018. We summarised the occurrences and

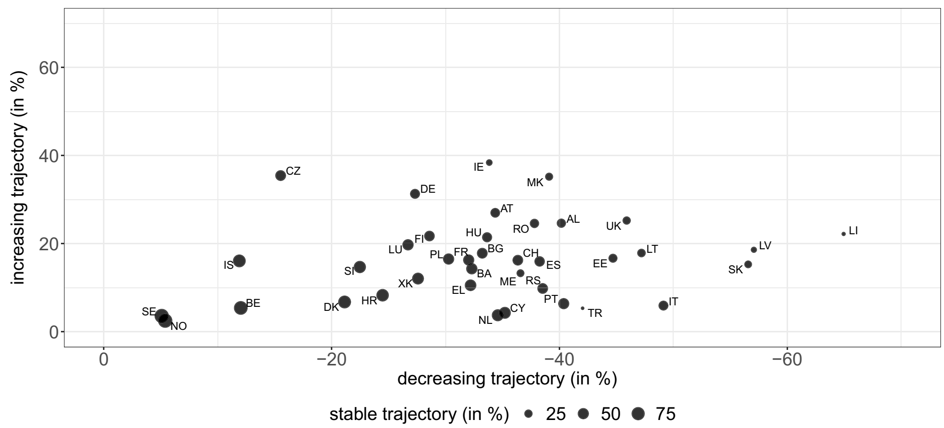

Fig. 2 Grassland development trajectories in the different European countries covered in this study. The two-letter country codes are based on the ISO 3166 standard for country identification

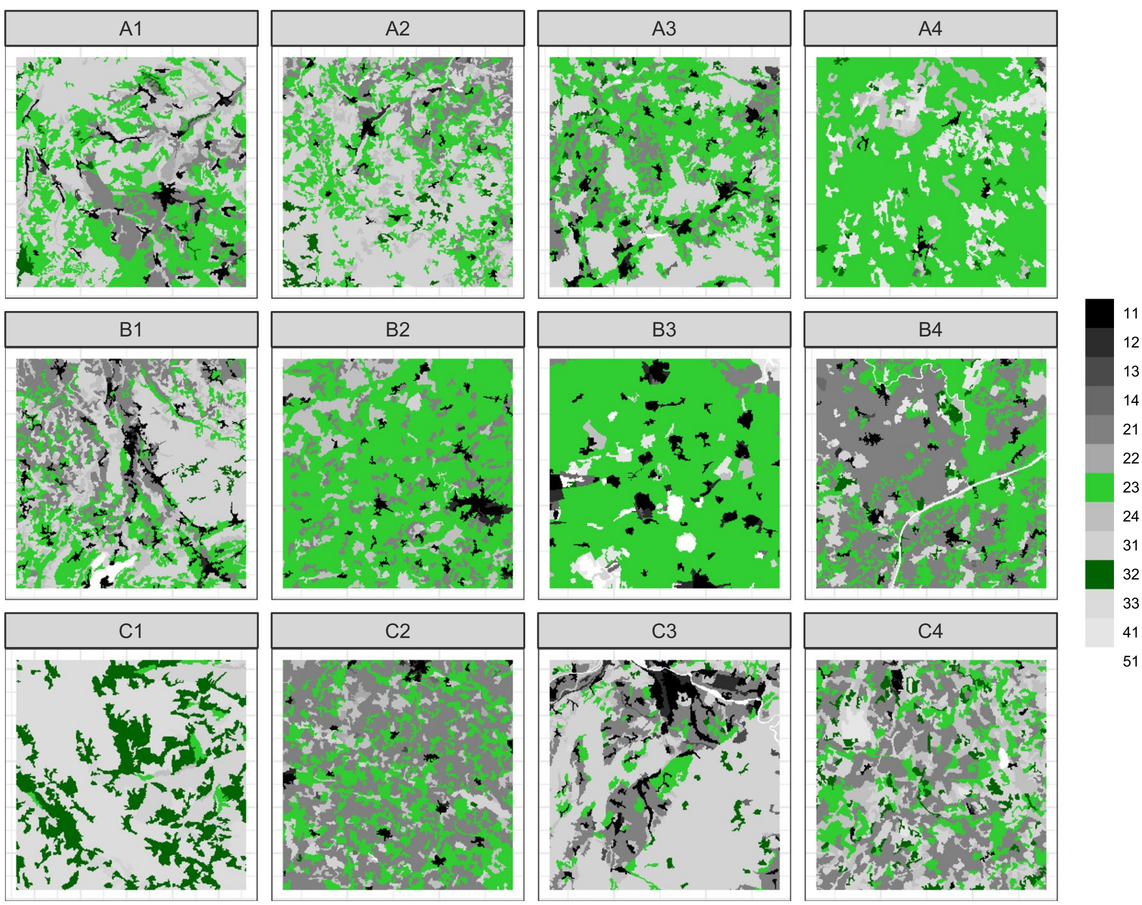

Fig. 3 Land cover in selected areas representing **A** increasing, **B** decreasing, **C** mixed grassland development trajectories. Grassland classes are highlighted in green colour, the grey shades stand for non-grassland land cover classes. The land cover classes are (11) urban fabric, (12) industrial, commercial and transport units, (13) mine, dump and construction sites, (14) artificial, non-agricultural vegetated areas, (21) arable land, (22) permanent crops, (23) pastures, (24) heterogeneous agricultural areas, (31) forests, (32) scrub and/or herbaceous vegetation associations, (33) open spaces with little or no vegetation, (41) inland wetlands and (51) inland waters

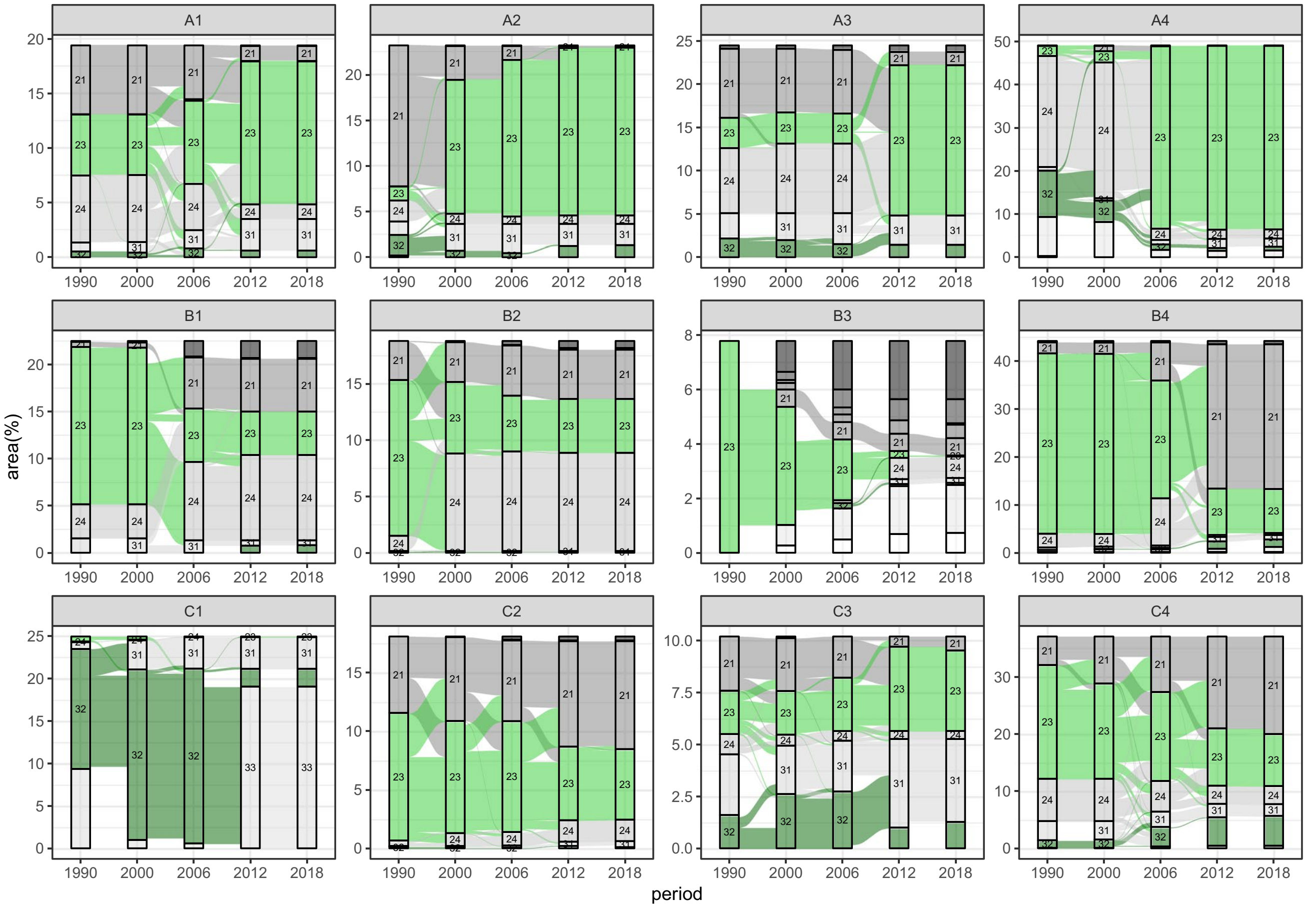

Fig. 4 Flowcharts of land cover change trajectories on selected areas representing **A** increasing, **B** decreasing, **C** mixed of grassland development trajectories. Grassland classes are highlighted in green colour, the grey shades stand for non-grassland land cover classes. The codes represent the land cover as follows: (11) urban fabric, (21) arable land, (22) permanent crops, (23) pastures, (24) heterogeneous agricultural areas, (31) forests, (32) scrub and/or herbaceous vegetation associations, (33) open spaces with little or no vegetation

changes in grassland areas within 1 km^2 grids, which enabled us to identify hotspots of grassland development trajectories across Europe. Although numerous studies have focused on the European-wide evaluation of land cover change hotspots (Kuemmerle et al. 2016), persistence (Lieskovský and Bürgi 2018), land change trajectories (Stürck et al. 2018), archetypal patterns and trajectories (Levers et al. 2018), our research adopts a unique approach, focused on the trajectories of specific land cover class.

We focused on grasslands, being one of Europe's most widespread land cover classes and are largely influenced by the dynamics of nature and human decisions. Prior research has explored the extent of grassland at the European scale in the context of the intensification and abandonment of agricultural production (Feranec et al. 2010; Alcantara et al. 2013; Estel et al. 2015). Both processes are important indicators of grassland change as grassland biodiversity faces a strong decline due to the intense change of agricultural production (Kuhn et al. 2021). In this paper, we used a different approach by focusing on the long-term development trajectories in gains and losses of grassland areas across Europe.

We found that grassland persistence was the most prevailing across Europe, with hotspots in intensively used lowland areas, such as the agricultural land in Belgium and the Netherlands. These grasslands are notable for high demand on multiple ecosystem services such as provisioning of fodder, grazing areas, recreational use, ecological corridors or cultural values (Gulickx et al. 2013; Estel et al. 2018). The observed spatial patterns are in line with the spatial patterns of persistence of human appropriation of net primary production derived based on CORINE land cover datasets (Plutzar et al. 2016) but showed different patterns from long-term European land cover persistence with the hotspots in the Alps, north and south Italy, north Ireland, Sweden, south Finland, Romania and the UK (Lieskovský and Bürgi 2018).

We also found that from 1990 to 2018, Europe has continuously lost a significant part of its grassland areas. The hotspots of declining trajectories were found in the former Eastern Bloc countries (such as the Baltic countries, Slovakia and Romania), where agricultural production collapsed after the breakdown of socialism and partly recovered only after decades (Griffiths et al. 2013; Pazúr et al. 2014). The recovery of agricultural production largely varied between countries and was largely related to the support gained from different subsidy schemes, such as the Common Agricultural Policies. The hotspots of declining trajectories were found in western England, northern Germany and the border regions of Austria. The trend of grassland decrease in western England was confirmed by the more detailed national-wide dataset and has been attributed to the expansion of the woodland and settlement structures (UKCEH 2020). In the case of Germany, similar areas of the northern part of the country have experienced in recent years an increase in land use intensities (mowing events) (Schwieder et al. 2022). Interestingly, an increase of the land use intensities within the areas of decreasing grassland extents was also found on selected study areas where grasslands have been transformed to permanent crops (e.g. fruit trees), arable land or were lost due to the expansion of settlement areas. Considering the natural values and ecosystem services the grassland provides, such losses negatively affect the species richness (Hilpold et al. 2018) and release the carbon stored in the grassland soils (Reinermann et al. 2020). Similarly, grassland transition towards other land cover classes often comes at cost of losses of the cultural heritage or cultural landscape (Plieninger et al. 2015).

Increasing development trajectories of the grassland areas have been found in central France, southern Germany and Ireland. These hotspots coincide with high mowing frequencies, as identified by the MODIS satellite (Estel et al. 2018), which may indicate the grasslands expansion in areas suitable for agricultural use. Such expansion may also be driven by the subsidy schemes where grassland management turned out to be the most supported agricultural land use strategy. For example, along the borders of the Czech Republic were croplands transformed into grassland mostly due to the subsidy schemes and ownership change (Kupková et al. 2021).

Observed grassland development trajectories demonstrate that national-wide policies likely formed the heterogeneity of grassland development across Europe. While the resulting maps highlighted spatial gradients in the grassland change across landscapes in Europe, we also identified the heterogeneity of the changes in the trends of grassland cover between the national borders. Examples may be found in the border region of the Netherlands and Germany, where the state border divided the observed trend between stable grasslands and grassland expansion, respectively. Similarly, between the state borders of Austria and Switzerland, we found that grassland simultaneously increased in the flat areas likely suitable for agriculture and has been overgrown by woody vegetation on some of the alpine meadows (Buchgraber et al. 2011), while alpine grasslands with similar bioclimatic conditions in eastern Switzerland appeared to be more stable.

Limitation of our study

Several factors may influence the accuracy of our maps and the interpretation of the outcomes. Firstly, the resulting maps are influenced by the mapping methodology of CORINE land cover datasets. The CORINE land cover dataset has a minimum mapping unit of 25 ha and a minimum identified change area size of 5 ha, which means that it is insensitive to small-scale changes (Diaz-Pacheco and Gutiérrez 2014; Pazúr et al. 2014; Cegielska et al. 2018). Additionally, the CORINE land cover mapping methodology has evolved over time, which can lead to inconsistencies in comparing the land cover patches across different periods (García-Álvarez and Camacho Olmedo 2017). Despite these limitations, the CORINE land cover has been proven to be a suitable land cover data source for land cover change mapping at the European level (Feranec et al. 2010; Hatna and Bakker 2011; Anderson and Mammides 2020). Secondly, our maps were produced on the aggregated data from their native 100-m pixel resolution to a 1 km^2 grid. This means we did not evaluate the inner dynamics of grassland change within each square grid. Consequently, some areas that were indicated as stable may exhibit dynamics within those 1km square grids. However, we assume that such patterns do not substantially influence the spatial variation of the mapped trajectories across Europe. Thirdly, the CORINE land cover datasets do not provide a continuous mapping but only cover specific points. This means that the mapping of the trends is based on five different time frames. Although available satellite-based data nowadays allows for continuous mappings of the land surface (Woodcock et al. 2020) based on the solid training data (EUROSTAT 2017) and robust classification models (Belgiu and Drăguţ 2016), we believe that for the time frame of 1990–2018, the CORINE land cover brings better accuracies on the European scale. This is because the CORINE land cover datasets result from a rigorous process of mapping and state-wide validation, which is managed by the European Union's Earth observation programme.

Considering the scale of this study, we certainly missed out on particular hotspots and important local specificities of grassland change. To encourage the readers to investigate the different trends in the CORINE land cover dataset, we have provided a link to a code in the supplementary material (Appendix B) that may be used to visualise the different CORINE land cover datasets and grassland datasets and download the European-wide maps of development trajectories of grassland cover. The code and related links are executable in the Google Earth Engine platform (Gorelick et al. 2017).

Conclusion

The proposed study highlights the different developmental trajectories of the grassland cover across Europe from 1990 to 2018. We used a specific methodology that summarised the trajectories across spatial and temporal scales. We found that, besides the persistence of grassland, the decrease of grassland areas was the most prevailing development trajectory, followed by the increased development trajectory of grassland areas. Using the Earth Observation data revealed that the patterns of the grassland development trajectories have certain spatial gradients across Europe. These gradients are often influenced by the national policies. Such findings indicate a need to define an EU-wide strategy better to target the preservation of grassland ecosystems in Europe. The Earth observation data can provide the necessary spatial information to better target policies on different hotspots of landscape change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-024-02197-5.

Funding Open Access funding provided by Lib4RI – Library for the Research Institutes within the ETH Domain: Eawag, Empa, PSI & WSL. This research was funded by the project of Swiss National Science Foundation No. CRSII5_183493: "What is Sustainable Intensification? Operationalizing Sustainable Agricultural Pathways in Europe (SIPATH)", by Biodiversa+, the European Biodiversity Partnership under the 2021-2022 BiodivProtect joint call project "G4B: Grasslands for biodiversity: supporting the protection of the biodiversity-rich grasslands and related management practices in the Alps and Carpathians", by the project of VEGA Grant Agency No. 2/0159/22: "Assessment of ecosystem services and their adaptation into the strategic planning and future development of the national parks and their hinterland", VEGA Grant Agency No. 2/0043/23: "Detection of landscape diversity and its changes in Slovakia based on remote sensing data in the context of the European Green Deal" and by the project of Slovak Research and Development Agency-21-0226: "Species-rich Carpathian grasslands: mapping, history, drivers of change and conservation" pursued at the Institute of Geography of the Slovak Academy of Sciences.

Data Availability Datasets generated during this study are accessible via the link listed in Appendix B.

References

Alcantara C, Kuemmerle T, Baumann M, Bragina EV, Griffiths P et al (2013) Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. Environ Res Lett 8:035035. https://doi.org/10.1088/1748-9326/8/3/035035

Alcantara C, Kuemmerle T, Prishchepov AV, Radeloff VC (2012) Mapping abandoned agriculture with multi-temporal MODIS satellite data. Remote Sens Environ 124:334–347. https://doi.org/10.1016/j.rse.2012.05.019

Anderson E, Mammides C (2020) Changes in land-cover within high nature value farmlands inside and outside Natura 2000 sites in Europe: A preliminary assessment. Ambio 49:1958–1971. https://doi.org/10.1007/s13280-020-01330-y

Belgiu M, Drăguţ L (2016) Random forest in remote sensing: A review of applications and future directions. ISPRS J Photogramm Remote Sens 114:24–31. https://doi.org/10.1016/j.isprsjprs.2016.01.011

Bengtsson J, Bullock JM, Egoh B, Everson C, Everson T et al (2019) Grasslands-more important for ecosystem services than you might think. Ecosphere 10:e02582. https://doi.org/10.1002/ecs2.2582

Bielecka E, Jenerowicz A (2019) Intellectual structure of CORINE land cover research applications in web of science: A Europe-wide review. Remote Sens 11:2017. https://doi.org/10.3390/rs11172017

Blüthgen N, Dormann CF, Prati D, Klaus VH, Kleinebecker CF et al (2012) A quantitative index of land-use intensity in grasslands: Integrating mowing, grazing and fertilization. Basic Appl Ecol 13:207–220. https://doi.org/10.1016/j.baae.2012.04.001

Bossard M, Feranec J, Oťaheľ J (2000) CORINE land cover technical guide – Addendum 2000, Copenhagen

Buchgraber K, Schaumberger A, Pötsch EM (2011) Grassland farming in Austria - status quo and future prospective. In: 16th Symp Eur Grassl Fed grassl Farming L Manag Syst Mt Reg, pp 13–24

Buchhorn M, Lesiv M, Tsendbazar NE, Herold M, Bertels L et al (2020) Copernicus global land cover layers-collection 2. Remote Sens 12:1–14. https://doi.org/10.3390/rs12061044

Cegielska K, Noszczyk T, Kukulska A, Szylar M, Hernik J et al (2018) Land use and land cover changes in post-socialist countries: Some observations from Hungary and Poland. Land use policy 78:1–18. https://doi.org/10.1016/j.landusepol.2018.06.017

Commission E for Agriculture D-G, Development R (2020) Evaluation of the impact of the CAP on habitats, landscapes, biodiversity : final report. Publications Office

Copernicus Land Monitoring Service (2020) Grassland 2018 and grassland change 2015-2018

Copernicus Programme (2021) The European union earth observation programme. Online

d'Andrimont R, Yordanov M, Martinez-Sanchez L, Eiselt B, Palmieri A et al (2020) Harmonised LUCAS in-situ land cover and use database for field surveys from 2006 to 2018 in the European Union. Sci Data 7:352. https://doi.org/10.1038/s41597-020-00675-z

Diaz-Pacheco J, Gutiérrez J (2014) Exploring the limitations of CORINE Land Cover for monitoring urban land-use dynamics in metropolitan areas. J Land Use Sci 9:243–259. https://doi.org/10.1080/1747423X.2012.761736

Estel S, Kuemmerle T, Alcántara C, Levers C, Prishchepov AV et al (2015) Mapping farmland abandonment and recultivation across

Europe using MODIS NDVI time series. Remote Sens Environ 163:312–325. https://doi.org/10.1016/j.rse.2015.03.028
Estel S, Mader S, Levers C, Verburg PH, Baumann M et al (2018) Combining satellite data and agricultural statistics to map grassland management intensity in Europe. Environ Res Lett 13. https://doi.org/10.1088/1748-9326/aacc7a
Eurostat (2015) LUCAS 2015. (Land Use/Cover Area Frame Survey)
EUROSTAT (2017) Lucas the Eu'S land use and land cover survey. 16. https://doi.org/10.18111/9789284419029
Feranec J, Jaffrain G, Soukup T, Hazeu G (2010) Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. Appl Geogr 30:19–35. https://doi.org/10.1016/j.apgeog.2009.07.003
Feranec J, Soukup T, Hazeu G, Jaffrain G (2016) European landscape dynamics: CORINE land cover data. CRC Press, Boca Raton, p 367
Fuchs R, Herold M, Verburg PH, Clevers JGPW, Eberle J (2015) Gross changes in reconstructions of historic land cover/use for Europe between 1900 and 2010. Glob Chang Biol 21:299–313. https://doi.org/10.1111/gcb.12714
García-Álvarez D, Camacho Olmedo MT (2017) Changes in the methodology used in the production of the Spanish CORINE: Uncertainty analysis of the new maps. Int J Appl Earth Obs Geoinf 63:55–67. https://doi.org/10.1016/j.jag.2017.07.001
Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D et al (2017) Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens Environ 202:18–27. https://doi.org/10.1016/j.rse.2017.06.031
Griffiths P, Müller D, Kuemmerle T, Hostert P (2013) Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union. Environ Res Lett 8:045024. https://doi.org/10.1088/1748-9326/8/4/045024
Griffiths P, Nendel C, Pickert J, Hostert P (2019) Towards national-scale characterization of grassland use intensity based on integrated Sentinel-2 and Landsat time series data. Remote Sens Environ 1–12. https://doi.org/10.1016/j.rse.2019.03.017
Gulickx MMC, Verburg PH, Stoorvogel JJ, Kok K, Veldkamp A (2013) Mapping landscape services : A case study in a multifunctional rural landscape in The Netherlands. Ecol Indic 24:273–283. https://doi.org/10.1016/j.ecolind.2012.07.005
Hatna E, Bakker MM (2011) Abandonment and expansion of arable land in Europe. Ecosystems 14:720–731. https://doi.org/10.1007/s10021-011-9441-y
Heymann Y (1994) CORINE land cover technical guide, Copenhagen
Hilpold A, Seeber J, Fontana V, Niedrist G, Rief A et al (2018) Decline of rare and specialist species across multiple taxonomic groups after grassland intensification and abandonment. Biodivers Conserv 27:3729–3744. https://doi.org/10.1007/s10531-018-1623-x
Huyghe C, De Vliegher A, Van Gils B, Peeters A (2014) Grasslands and herbivore production in Europe and effects of common policies. éditions Quae
Isselstein J, Kayser M (2014) Functions of grassland and their potential in delivering ecosystem services. In: EGF 50 Futur Eur grasslands Proc 25th Gen Meet Eur Grassl Fed Aberystwyth, Wales, 7-11 Sept 2014, pp 199–214
Kolecka N, Ginzler C, Pazur R, Price B, Verburg PH (2018) Regional scale mapping of grassland mowing frequency with sentinel-2 time series. Remote Sens 10:1221. https://doi.org/10.3390/rs10081221
Kuemmerle T, Levers C, Erb K, Estel S, Jepsen MR et al (2016) Hotspots of land use change in Europe. Environ Res Lett 11:064020. https://doi.org/10.1088/1748-9326/11/6/064020
Kuhn T, Domokos P, Kiss R, Ruprecht E (2021) Grassland management and land use history shape species composition and diversity in Transylvanian semi-natural grasslands. Appl Veg Sci 24:1–12. https://doi.org/10.1111/avsc.12585
Kupková L, Bičík I, Jeleček L (2021) At the crossroads of european landscape changes: Major processes of landscape change in czechia since the middle of the 19th century and their driving forces. Land 10:1–25. https://doi.org/10.3390/land10010034
Levers C, Müller D, Erb K, Haberl H, Jepsen Rudbeck M et al (2018) Archetypical patterns and trajectories of land systems in Europe. Reg Environ Chang 18:715–732. https://doi.org/10.1007/s10113-015-0907-x
Lieskovský J, Bürgi M (2018) Persistence in cultural landscapes: a pan-European analysis. Regioanal Environ Chang 18:175–187. https://doi.org/10.1007/s10113-017-1192-7
Müller D, Kuemmerle T, Rusu M, Griffiths P (2009) Lost in transition: determinants of post-socialist cropland abandonment in Romania. J Land Use Sci 4:109–129. https://doi.org/10.1080/17474230802645881
Munteanu C, Kuemmerle T, Boltiziar M, Van B, Gimmi U et al (2014) Forest and agricultural land change in the Carpathian region—A meta-analysis of long-term patterns and drivers of change. Land Use Policy 38:685–697. https://doi.org/10.1016/j.landusepol.2014.01.012
O'Brien CD, Di Gregorio A, Mushtaq F, Henry M, Tchana E et al (2021) Register implementation for land cover legends. FAO and UoS and STIIMA-CNR
Pazúr R, Lieskovský J, Bürgi M, Müller D, Lieskovský T et al (2020) Abandonment and recultivation of agricultural lands in Slovakia-patterns and determinants from the past to the future. Land 9. https://doi.org/10.3390/LAND9090316
Pazúr R, Lieskovský J, Feranec J, Oťaheľ J (2014) Spatial determinants of abandonment of large-scale arable lands and managed grasslands in Slovakia during the periods of post-socialist transition and European Union accession. Appl Geogr 54:118–128. https://doi.org/10.1016/j.apgeog.2014.07.014
Peeters A (2012) Past and future of European grasslands. The challenge of the CAP towards 2020. In: Goliński P, Warda M, Stypiński P (eds) Grassland - a European resource? Proceedings of the 24th General Meeting of the European Grassland Federation, Lublin, Poland, 3–7 June 2012. European Grassland Federation, Poznan, pp 17–32
Pflugmacher D, Rabe A, Peters M, Hostert P (2019) Mapping pan-European land cover using landsat spectral-temporal metrics and the European LUCAS survey. Remote Sens Environ 221:583–595. https://doi.org/10.1016/j.rse.2018.12.001
Plieninger T, Bieling C, Fagerholm N, Byg A, Hartel T et al (2015) The role of cultural ecosystem services in landscape management and planning. Curr Opin Environ Sustain 14:28–33. https://doi.org/10.1016/j.cosust.2015.02.006
Plutzar C, Kroisleitner C, Haberl H, Fetzel T, Bulgheroni C et al (2016) Changes in the spatial patterns of human appropriation of net primary production (HANPP) in Europe 1990–2006. Reg Environ Chang 16:1225–1238. https://doi.org/10.1007/s10113-015-0820-3
Prishchepov AV, Müller D, Baumann M, Kuemmerle T, Alcantara C et al (2017) Underlying drivers and spatial determinants of post-soviet agricultural land abandonment in temperate eastern Europe. In: Land-cover and land-use changes in Eastern Europe after the collapse of the Soviet Union in 1991. Springer International Publishing, Cham, pp 91–117. https://doi.org/10.1007/978-3-319-42638-9_5
Reinermann S, Asam S, Kuenzer C (2020) Remote sensing of grassland production and management—A review. Remote Sens 12:1949. https://doi.org/10.3390/rs12121949
Schils RLM, Bufe C, Rhymer CM, Francksen RM, Klaus VH et al (2022) Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. Agric Ecosyst Environ:330. https://doi.org/10.1016/j.agee.2022.107891
Schwieder M, Wesemeyer M, Frantz D, Pfoch K, Erasmi S et al (2022) Mapping grassland mowing events across Germany based on combined sentinel-2 and landsat 8 time series. Remote Sens Environ 269:112795. https://doi.org/10.1016/j.rse.2021.112795

Stürck J, Levers C, van der Zanden EH, Schulp CJE, Verkerk PJ et al (2018) Simulating and delineating future land change trajectories across Europe. Reg Environ Chang 18:733–749. https://doi.org/10.1007/s10113-015-0876-0

UKCEH (2020) Land cover change 1990-2015 dataset documentation

Weigand M, Staab J, Wurm M, Taubenböck H (2020) Spatial and semantic effects of LUCAS samples on fully automated land use/land cover classification in high-resolution Sentinel-2 data. Int J Appl Earth Obs Geoinf:88. https://doi.org/10.1016/j.jag.2020.102065

Woodcock CE, Loveland TR, Herold M (2020) Preface: time series analysis imagery special issue. Remote Sens Environ 238:111613. https://doi.org/10.1016/j.rse.2019.111613

Zhao Y, Liu Z, Wu J (2020) Grassland ecosystem services: a systematic review of research advances and future directions. Landsc Ecol 35:793–814. https://doi.org/10.1007/s10980-020-00980-3