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Dynamic archetypes of agricultural land systems in Germany from 1992 to 2019

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ABSTRACT

Grasslands, important agricultural land systems, are undergoing significant shifts such as intensification, abandonment, and conversion to alternative land uses in Europe, leading to biodiversity loss. Despite major efforts, the European Union's Common Agricultural Policy (CAP) has been unable to halt the decline of grasslands and to appropriately adjust management intensity because implemented policies have not considered the heterogeneity of grassland systems. However, accounting for this heterogeneity is essential to increase the policies′ effectiveness. In this study, we used archetype analysis to identify recurrent patterns in the heterogeneity of farm configurations, using Germany as an example, that can help tailor policy instruments to specific regional conditions. By applying self-organising maps, we reveal nine archetypes integrating 16 farm accountancy indicators. Advancing archetype analysis, we discuss their dynamics (including their emergence, disappearance and persistence) between 1992 and 2019 at the level of federal states and interpret these dynamics in the light of CAP. For example, archetypes in the western federal states are dominated by small crop and dairy farms, while archetypes in the eastern federal states are more diverse, including larger subsidised farms and medium crop farms. Moreover, archetype dynamics in the southern federal states indicate a decline in small dairy farms and an increase in small crop farms, implying the loss of valuable habitats for wild species. Policy instruments tailored to such regional conditions could more appropriately halt this loss. These insights derived from agricultural land systems in Germany can enrich the debate about how to better tailor policy instruments to regional conditions to preserve functional grassland systems in Europe and worldwide.

1. Introduction

Agricultural land systems in Europe face diverging shifts towards intensification and specialisation, conversion into species-poor, higher-yielding land use alternatives (such as cropland), marginalisation and abandonment (Vogt et al., 2019). Despite efforts to increase support for sustainable land management, uniformly defined policy instruments within the European Union's (EU) Common Agricultural Policy (CAP) have been limited in their effectiveness in addressing different grassland management systems and strategies (Pe'er et al., 2022). One reason is that they do not adequately consider the diversity of farms and regional specificities (Sietz et al., 2022). Hence, the constant decline of grasslands in Europe since 1975 (Smit et al., 2008) and the increase in management intensity could not be halted or even reversed. Exemplifying this trend, Germany's cultivated permanent grasslands declined from 5.6 million ha in 1990 to 4.7 million ha in 2021 (Destatis, 2022).

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This trend is expected to continue and can have severe socio-ecological consequences. Besides their importance for agricultural production, grasslands provide essential ecosystem services such as habitats for wild species, carbon sequestration, protection against erosion and flooding, and a basis for nature-related recreation and tourism, contributing to rural economy and development (Bai and Cotrufo, 2022; Hussain et al., 2019; Orozco and Grundmann, 2022; Schils et al., 2022).

How policy instruments evolve can significantly influence the management of grasslands towards reaching a desired direction or preventing an undesirable development (Orozco et al., 2021). The post-2020 CAP aims to meet the EU's social, environmental, and economic objectives leading to the creation of political instruments to halt the decline of grassland at European and national levels (Schils et al., 2022). For example, grassland protection was integrated into the CAP cross-compliance system. Moreover, the CAP provides subsidies for both temporary and permanent grasslands. The current CAP 2023–27 defines standards of Good Environmental and Agricultural Condition (GAEC) to address environmental objectives by restricting the conversion of grassland (GAEC 1) and protecting ecologically sensitive grassland (GAEC 10). Since 2006, some federal states in Germany have enacted laws to prevent a further decline of grassland. These were replaced in 2015 by (less strict) regulations as part of greening efforts (Lakner and Holst, 2015). However, the diversity of grasslands still challenges the success of these policies.

The conditions of grasslands vary depending on management intensity and biophysical factors, such as climate and soils (Chang et al., 2021; Neyret et al., 2021). Grasslands in Germany usually occur in less productive sites, as more fertile land is typically used for crop production (Bruns et al., 2000). In addition, distinct farming systems are characterised by different field- and farm-level agricultural practices, which reflect farmers' decisions on land use, labour input, crop selection and livestock density (Martin et al., 2020; Santos et al., 2021). Although agricultural land systems are unique if described in sufficient detail, they typically show similarities in their attributes (Dou et al., 2021; Wolff et al., 2021). These similarities have inspired the investigation of archetypes (Eisenack et al., 2021; Oberlack et al., 2019). Archetypes are defined as recurrent patterns of the phenomenon of interest at an intermediate level of abstraction (Oberlack et al., 2019). Archetype analysis helps to bridge the gap between policies designed at national or higher levels and the specific configurations of farming systems at regional levels as it enables the tailoring of land use policies to typical characteristics of land systems (Oberlack et al., 2023; Sietz et al., 2022).

Previous studies of archetypical patterns of agricultural land systems have focused on the level of individual pixels, sometimes exploring patterns of land use change (Lüdeke et al., 2014; Levers et al., 2018; Zarbá et al., 2022), at nested scales (Sietz, Ordoñez, et al., 2017) or at the farm level (Tittonell et al., 2020; Vidal Merino et al., 2019) including structure, management intensity and value of agricultural landscapes (Vaclavik et al., 2024). Yet, previous studies often have a limited temporal frame and analyse patterns of land use systems independent of policy impacts. This limits our knowledge and capacity to increase the effectiveness of agricultural policies.

To address this knowledge gap, this paper aims to improve our understanding of the relationship between archetypes of agricultural land systems and agricultural policies by posing the following research questions. Firstly, are there archetypical patterns in the factors and processes that have shaped agricultural land systems in Germany, specifically grassland systems? Secondly, how can the dynamics of these patterns be interpreted in the light of CAP policy changes?

We investigated grassland system archetypes in Germany using 16 farm-level accountancy indicators. We applied self-organising maps (SOMs) to data from 1992, 2003, 2013 and 2019 reflecting the importance of CAP policy changes. The regional distribution of archetypes is mapped for each year at the level of the 16 federal states in Germany. The regional dynamics at the level of federal states involved the emergence, disappearance and persistence of archetypes. Finally, the changes in grassland system archetypes are discussed in the light of policy developments and core changes in the CAP.

2. Materials & methods

2.1. Policy context of grasslands in Germany

We focused our analysis on the years 1992, 2003, 2013 and 2019, reflecting core reforms in policy instruments in the CAP that markedly influenced Europe's land use and market structure. Table 1 provides a timeline of the diverse reforms and instruments of the CAP relevant to grassland systems in the last thirty years. In addition, the associated milk market environment and effects of the policy instruments on the dairy market are presented.

The German agricultural policy, driven by the CAP, has evolved significantly over the years. Initially focused on productivity growth, income support, and market stabilisation, the CAP underwent major reforms in the early 1990s, leading to substantial impacts on land use, particularly grasslands. Various CAP instruments, such as direct payments, rural development measures, and agri-environmental measures, play a crucial role in grassland management. Rules for maintaining permanent pasture have been established under the CAP through eligibility criteria and minimum requirements tied to receiving direct payments. The provisions and voluntary schemes by the CAP (Pillar II) have been used partly to promote the conversion from marginal arable land to permanent grasslands. With cross-compliance, the EU set minimum

Table 1
Policy and market environment in the reference years of this study.

	Policy environment	Market environment
1992	Prior to the MacSharry-Reform of 1992 subsidies were granted through a high intervention price. Protective tariff rates were still in place (Daugbjerg, 2003).	Higher intervention prices for milk were in place. The milk quota was applied, disincentivising investment. Quota could not be traded (Kerckow, 1993).
2003	CAP-scenario post Agenda 2000, but prior to the Fischler-Reform and the decoupling of direct payments. Direct payments existed with specific coupled payments for suckler-cows, bulls, and cattle. No specific payments for grassland. Some first agri-environmental payments were in place (Bergmann et al., 2015).	Intervention prices also decreased for milk, butter and skimmed milk powder. The buying and selling of quotas began in 2000 on a regional basis, which might lead to shifts from marginal regions to more intensive regions (Jongeneel and Gonzalez-Martinez, 2022).
2013	The Fischler-Reform 2005–2008 and the Health-Check-Reform (2009–2013) were fully implemented. This meant that decoupling of direct payments in Germany was applied, and the regional payment model was fully implemented, which provided decoupled direct payments for grassland and therefore favours milk- and suckler-cow farms. In most federal states, laws restricted the conversion of grassland (Swinnen and Centre for European Policy Studies, 2008).	The milk-quota was still in place but ran out in 2015 (Jongeneel and Gonzalez-Martinez, 2022). Quota could be traded on a national level. Relatively favourable market conditions: A substantial demand for milk from the world market led to high milk-prices (Destatis. 2018a, 2018b).
2019	The effects of the Ciolos-Reform were becoming visible, including the application of greening and less stringent rules for grassland conversion (Sodano and Gorgitano, 2021).	Difficult market environment: The milk quota was abolished in March 2015 (European Commission, 2016). Together with a lower export demand from China and the Russia-embargo from 2014, prices substantially dropped in 2014/15. In 2017, the EU-Commission intervened in the milk-market, stabilising the prices (European Commission, 2016, 2019).

standards for the protection of permanent grassland. Altogether, the EU's financial support has promoted the intensification of plant and livestock production to enhance farm performance. Yet, this approach may not be suitable for all farming systems in Germany due to their diversity.

2.2. Dynamic archetype analysis

The treatment of temporal dynamics is a key aspect of archetype analysis (Sietz et al., 2019). Dynamic archetype analysis seeks to reveal how recurrent patterns change over time, in contrast to approaches that account for time only implicitly or do not refer to time at all (Sietz et al., 2019). Essentially, dynamic archetype analysis enables the generalisation of interactions and dynamics of co-evolving processes, delivering insights to inform the debate about possible transitions toward enhanced sustainability.

However, only a few archetype studies have captured pattern changes over time. These used time-series data or modelling approaches to assess the development trajectories of social-ecological systems (Sietz et al., 2019). For example, dynamics in archetypical patterns of dryland vulnerability (Lüdeke et al., 2014), archetypical changes in land systems (Levers et al., 2018) and archetypes of ecosystem service trajectories depending on land use intensity (Locatelli et al., 2017) were assessed using cluster analysis and self-organising maps (SOMs). In these studies, either static archetypes were identified at several points in time and trends in the functional relations and spatial distribution were assessed, or archetypical changes in variables were revealed. Other studies investigated temporal archetype aspects seeking to better understand generic system behaviour, including feedback loops. For example, agricultural land transformation was forecasted using system dynamics modelling based on system archetypes found in policy scenarios (Turner et al., 2017). These models were used to simulate complex dynamic systems and to evaluate and revise policies. They help to unravel influential factors, their relations and structural changes which may direct a system's behaviour in a desired way. However, identifying influential parameters and leverage factors is challenging, and system inertia may limit the predictability of long-term system behaviour.

In this study, we used SOMs to identify archetypical patterns of grassland systems in Germany and investigate changes in the indicator configurations that characterise the archetypes in the period between 1992 and 2019. We then discuss how amendments in the CAP may have contributed to changes in these patterns.

2.3. Data and indicator selection

We used 16 indicators obtained from the Farm Accountancy Data Network (FADN). The FADN database consists of accounting data from representative farms in Europe. It provides economic indicators and is, therefore, an important data source for analysing the dynamics and impacts of agricultural policy instruments on socio-ecological systems (Neuenfeldt and Gocht, 2012). These data are particularly useful for dynamic archetype analysis because they have been published annually since 1992.

We selected indicators that have a direct connection to grassland systems. We disregarded those indicators without any explicit relation such as e.g., wine production, fuel consumption, voluntary work, woodland area, farmhouse consumption, etc., retaining a total of 65 variables. We standardised all indicators based on their mean and standard deviation (z-scaling) to ensure consistent mean-centering and unit scale differences as a basis for comparison. To avoid collinearity in the input data, we investigated Pearson correlation coefficients between the z-scaled variables. Of those indicators that were highly correlated ($r < -0.85$ or $r > 0.85$), only one of each pair was retained. This further reduced the data set to 25 indicators.

To ensure the use of indicators that hold most of the information in the dataset (Sietz et al., 2012), we applied a Principal Component Analysis (PCA) separately for each year. We selected the indicators with the highest loadings in each year's first three principal components (PCs) and kept 16 out of 25 indicators. These indicators (Table 2) explained 90 % of the total variance in the data. The number of observations or representative farms was 4689 in 1992, 5965 in 2003, 7982 in 2013 and 8260 in 2019. In 1992, FADN data covered only western Germany, which explains this year's lower number of representative farms. The selected 16 indicators reflect political support (subsidies and direct payments), land-use decisions (arable land, permanent grassland, pasture and meadows), economic aspects (forage, livestock units, crop production, milk yield) and type of farming (labour input, goats, ewes, stocking density) (see Appendix A for a detailed description of the selected indicators).

2.4. Identification of agricultural land system archetypes and their dynamics

We used SOMs to cluster the 16-dimensional data space into archetypical patterns of grassland systems in Germany in 1992, 2003, 2013 and 2019. We then assessed the dynamics in these archetypes over time.

Table 2
Indicators used for the classification of dynamic archetypes of agricultural land systems (Note: Bold indicator names are used in Fig. 1 and Fig. 2 to facilitate their retrieval.).

Indicator	Unit	Description
Unpaid Labour	hours	Time worked in hours by unpaid labourers (generally family).
Paid Labour Input	hours	Time worked in hours by total labourers.
Ewes, Breeding females	average number	Number of ewes and breeding females.
Goats, other goats, ewes **and sheep**	units	Number of goats, other goats, ewes, and other sheep.
Stocking density	unit/ha	Density of ruminant grazing livestock.
Total **livestock units**	units	Number of cattle, sheep, goats, pigs and poultry converted into livestock units.
Milk yield	kg/cow	Average milk production and milk products (in milk equivalents) in kg per dairy cow. Production includes farmhouse consumption and farm use (distributed to animals). Holdings without dairy cows are excluded.
Total **output crops** & crop production (EUR)	EUR	Sum of sales, farm use, farmhouse consumption and the difference between the closing valuation and the opening valuation.
Agricultural land not cultivated	ha	Agricultural land not cultivated for agricultural purposes.
Forage	ha	Area of fodder plants.
Pasture and Meadow	ha	Temporary grass, meadows and permanent pastures, rough grazing.
Total **utilised agricultural area**	ha	Total utilised agricultural area of holding.
Permanent grassland	ha	Area of permanent grassland and permanent pasture.
Arable land	ha	Land cultivated for crop production or areas available for crop production.
Total **direct payments**	EUR	National decoupled and coupled subsidies.
Total subsidies	EUR	Total subsidies.

SOMs are a clustering technique based on artificial neural network algorithms especially suited for revealing patterns in high-dimensional data spaces. They reduce the complexity of a given data space to a predefined two-dimensional output plane, grouping cases into sets with similar properties. SOMs are well established in the methodological portfolio of archetype analysis and can be applied at any spatial or temporal scale (Sietz et al., 2019). They have been used previously to identify archetypes of land systems in Europe (Beckmann et al., 2022) and bundles of ecosystem services in Germany (Dittrich et al., 2017).

Being an unsupervised learning approach, SOMs do not rely on predefined classes and hence contrast classification methods that use expert-defined thresholds to group data (Dou et al., 2021). Yet, SOMs rely on statistical analysis and hence do not reveal causal relationships. In contrast, process-centered meta-analyses of case studies retain causal relationships during the synthesis process (Meyfroidt et al., 2014). However, they are restricted to small sample sizes to support in-depth analysis. This narrows the set of cases that can be generalised to draw causal inferences. Moreover, comparable case studies are often scarce, and coding causal factors, mechanisms and related outcomes is demanding. Among the modelling approaches to archetype analysis, system dynamics models can reveal non-linear dynamics in causal mechanisms (see Sietz et al., 2019 for a review). However, they require explicit assumptions about the a priori constructed mental models and empirical evidence to parametrise the models (Turner et al., 2017). Although SOMs do not directly address temporal changes or processes, they help to identify structures in multi-year data spaces and can reveal unexpected patterns.

We ran the SOM analysis using the selected indicators to identify archetypes at the level of representative farms. The SOM analysis was computed with standardised (z-scaled) input data, which allowed the integration of indicators with diverse units and the interpretation of indicator values for each cluster in terms of positive and negative deviation from the national (German) mean value represented by zero.

SOM analysis requires a prior definition of the size of the two-dimensional output plane. Defining a high number of clusters may force the algorithm to split relatively homogeneous clusters, while choosing a low number of clusters may result in clusters that are too heterogeneous. Therefore, we tested 20 different cluster dimensions (from 2 to 36), organised in differently shaped output planes (e.g. 1 by 4 versus 2 by 2). The optimal number of clusters was determined separately for each year combining two aspects. First, the 'elbow method' was used to identify the level of decrease in the mean distance of the samples to the centre of the cluster to which the samples were assigned (Wehrens and Kruisselbrink, 2018). Second, we assessed the increase in the ratio of intra- and inter-cluster variability, expressed as the Davies–Bouldin index (Davies and Bouldin, 1979), to find SOM partitions with compact and well-separated clusters. We interpreted the resulting clusters, i.e. the typical combinations of indicator values at the cluster centres, as archetypes of grassland systems.

We visualised the combinations of indicator values at each cluster centre in the form of bar plots. We also evaluated the quality of cluster results by calculating the quantisation error (i.e. the distance of each sample to the cluster centre), which indicates how homogeneous the clusters are and whether outliers exist that do not fit their cluster closely

Table 3
Characteristics of agricultural land system archetypes in Germany.

Number	Archetype	Description	Year	Share of archetype per year (%)	Main occurrence
1	*Small ruminant farm*	• highest number of goats, sheep and ewes • small size farm	1992 2003 2013 2019	0.8 0.5 0.5 0.4	NRW, NI TH S, SH SH, NRW
2	*Small crop farm*	• low-yield crop production • unpaid labour	1992 2003 2013 2019	22.5 42.3 46.6 50.8	BY, NI NS, BY, NRW NS, BY, NRW, BW BY, NRW, NI
3	*Small dairy farm*	• small, milk-producing farm with highest stocking density of ruminants (due to small total area) • Average unpaid labour	1992 2003 2013 2019	42.6 47.1 32.4 34.4	BY, BW, NI, NRW BY, NI BY BY, NI, NRW
4	*Extensive grazing farm*	• large area of permanent pasture, temporary pasture/meadow and forage • high milk yields • average stocking density	1992 2003 2013 2019	17.4 6.1 11.5 6.9	HS, SH BY, SA, NS NI NI
5	*Crop farm and uncultivated land*	• crop production • largest uncultivated area • lowest total livestock units	1992 2003 2013	4.4 2.0 3.2	HS SH SH, NI
6	*Medium mixed farm*	• high crop production • above-average total livestock units • below-average dairy production • high paid labour input	1992	12.3	NRW, NI, BY
7	*Large subsidised mixed farm*	• largest agricultural area • highest total livestock units • highest total subsidies • highest paid labour input	2003 2013 2019	2.2 1.6 1.8	BB, SA, S S S
8	*Mixed farm*	• largest area of permanent pasture and pastures and meadows • very large forage area • High total livestock units • High subsidies	2013	1.4	S, MV, TH
9	*Medium crop farm*	• Very high crop production • Above-average agricultural area • Above-average total subsidies	2013 2019	2.9 5.7	MV, SA, BB, TH SA, MV, BB

(Abbreviation for German federal states: Baden-Wuerttemberg (BW), Bavaria (BY), Brandenburg (BB), Hamburg (H), Hesse (HS), Mecklenburg-Western Pomerania (MV), Lower Saxony (NI), Nord Rhine-Westphalia (NRW), Rhineland-Palatinate (RP), Saarland (SL), Saxon (S), Saxony-Anhalt (SA), Schleswig-Holstein (SH), Thuringia (TH))

(Davies and Bouldin, 1979). Finally, we mapped the clusters' distribution across the 16 federal states constituting Germany to assess their regional distribution and dynamics over the considered years. We used R 4.3.1 ("Beagle Scout") for all data processing and analyses, and the kohonen 3.0.12 package (Wehrens and Kruisselbrink, 2018) to implement the SOM clustering.

3. Results

We derived a total of 9 agricultural land system archetypes characterised by different configurations of the 16 selected indicators (Table 3, Fig. 1 and Fig. 2). Table 3 summarises the characteristics of all archetypes together with a brief explanation. It presents the year in which an archetype appears and its share among all archetypes found in a given year. We named the archetypes according to outstanding indicator values (i.e. minima and maxima) across all archetypes and their combinations. The federal states where archetypes are mainly found in a given year are also listed. Fig. 3 shows their regional distribution.

The six different archetypes identified in 1992 are shown in Fig. 1 (see Appendix B for the barplots of 2003,2013 and 2019). The first archetype, called *"Small ruminant farm",* is characterised by the highest number of goats, sheep and ewes. Besides the small amount of crops produced (see indicator 'output crop' in Fig. 1) on the existing arable land, this type of farm is also characterised by small areas of uncultivated land. The second archetype *"Small crop farm"* is characterised by an average crop yield (see indicator 'output crop' in Fig. 1). The utilised agricultural area, milk yield and stocking density are well below the national average. The third archetype *"Small dairy farm"* is characterised by a below-average total utilised agricultural area and average pasture and meadow area though above-average milk yield and stocking density of ruminant grazing livestock, as is expected for dairy farms. The high stocking density results from the small total utilised agricultural area. Furthermore, the variable of unpaid labour is relatively high compared to other archetypes, indicating smaller, potentially family farms. In the fourth archetype *"Extensive grazing farm",* farmers manage above-average amounts of permanent grassland, arable land, temporary pastures and meadows, and forage. Due to the extensive land area, stocking density is at an average value. At the same time, this archetype receives a slightly above-average share of agricultural subsidies.

The fifth *"Crop farm and uncultivated land"* archetype is characterised by above-average crop production and highest values of uncultivated areas. Total livestock units are below-average with absent goats and sheep. The five archetypes above persisted throughout all years. In contrast, the sixth archetype *"Medium mixed farm"* was only found in 1992. This type of farm combines crop and livestock production. It is characterised by a comparatively high crop production, just above-average total livestock units and comparably high paid labour input. Compared with the other archetypes, the 'mixed farm' archetype represents medium-sized farms, which keep animals but no dairy cows.

3.1. Changes, similarities, and highlights in 2003, 2013 and 2019

While the archetype *"Medium mixed farm"* was only found in 1992, a new archetype called *"Large subsidised mixed farm"* emerged in 2003 in the eastern federal states and persisted there until 2019 (Fig. 2). This

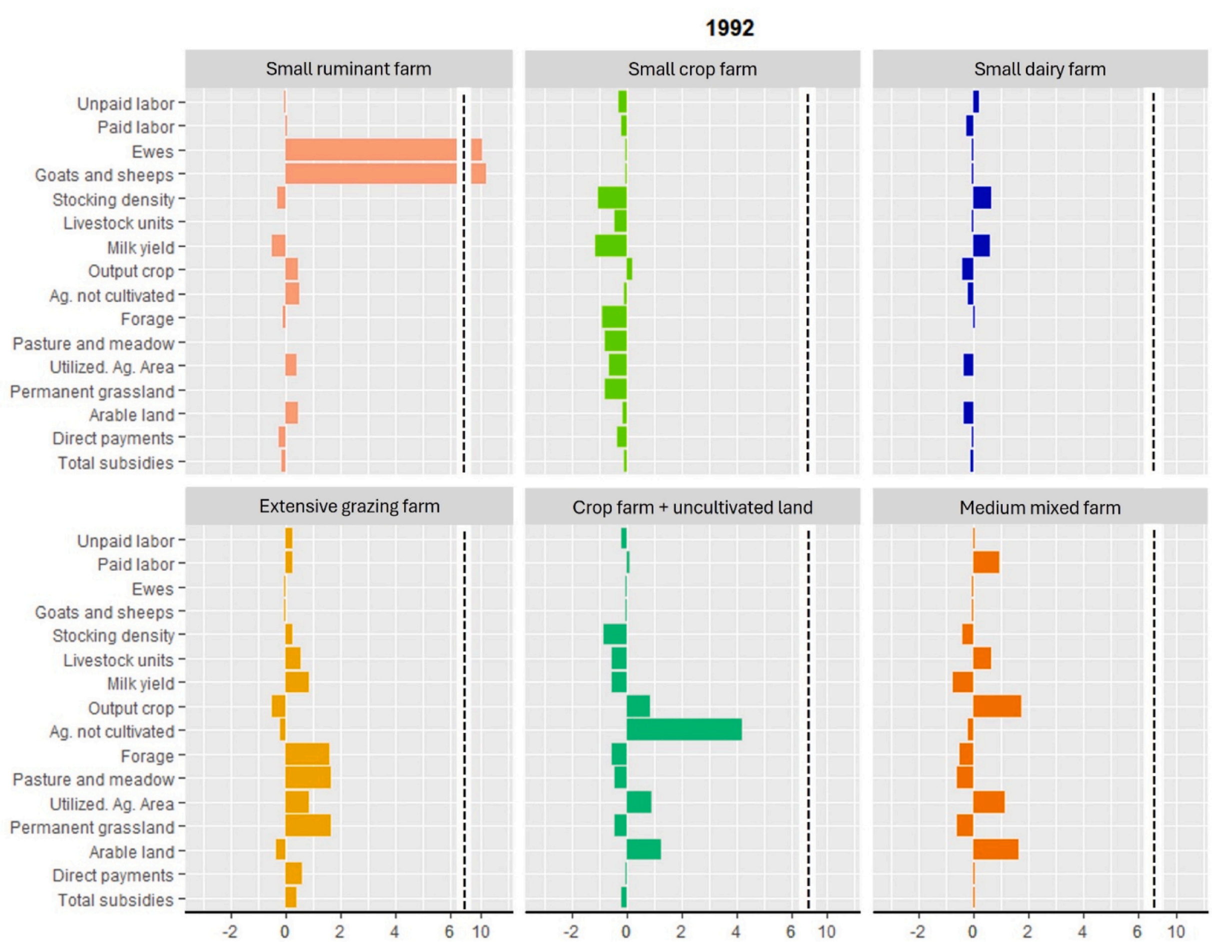

Fig. 1. Archetypes of agricultural land systems in 1992. (Note: At the x-axes, 0 indicates the national average for Germany in a given year. Below and above average values indicate deviations from the national average value.).

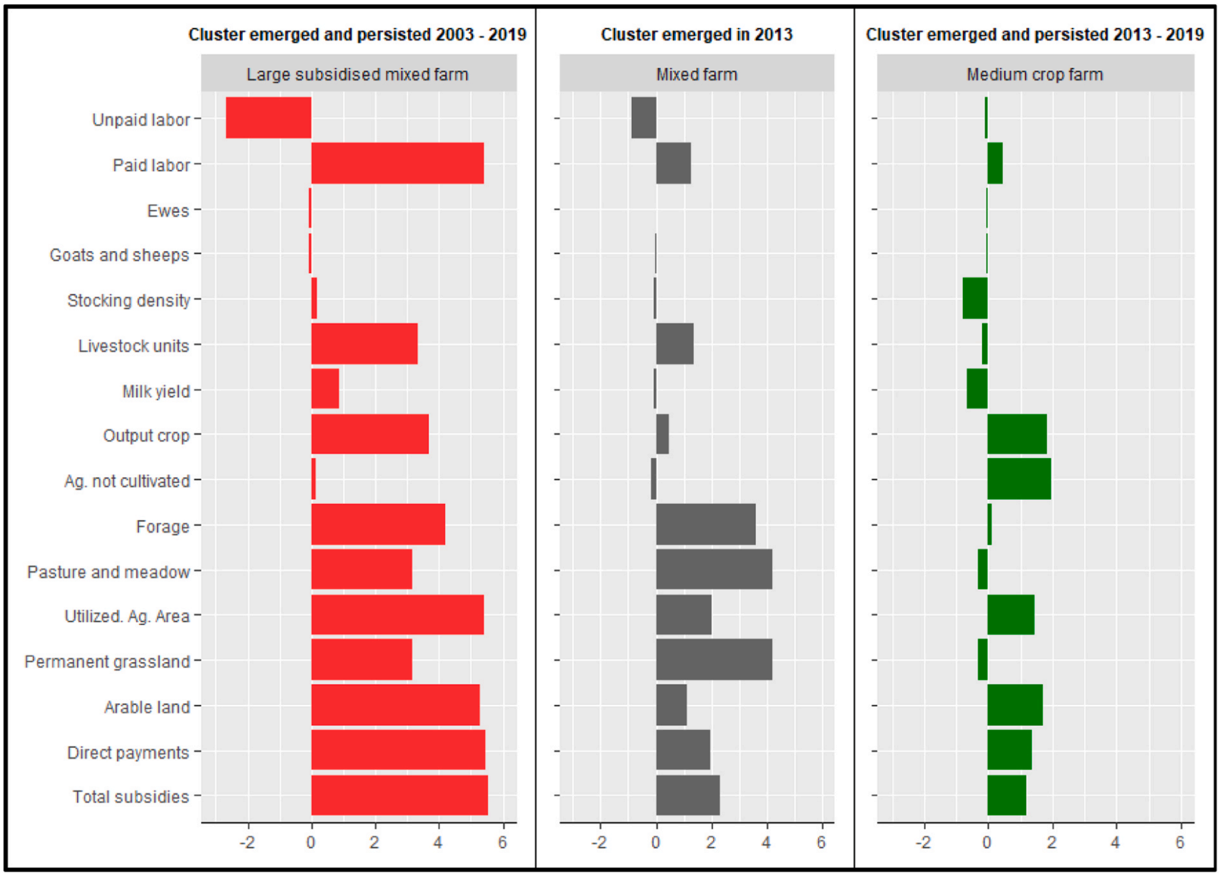

Fig. 2. Newly emerged archetypes of agricultural land systems in 2003, 2013 and 2019 (Note: Barplots show archetypical combinations of indicator values at cluster centres in 1992, 2003, 2013 and 2019. At the x-axes, 0 indicates the national average for Germany in a given year. Below and above average values indicate deviations from the national average value.).

archetype is characterised by maximum values of subsidies, the largest area of agricultural land for all types of land use and the highest total number of livestock units. Furthermore, this archetype depicts the highest input of paid labour.

A total of six archetypes were identified in 1992, 2003 and 2019, while eight archetypes were identified in 2013. Two new archetypes emerged in 2013 (Fig. 2). These are called *"Mixed farm"* and *"Medium crop farm"*. The *"Mixed farm"* archetype is characterised by an (slightly) above-average amount of crop and livestock production accompanied by large areas of permanent grasslands and pastures. In contrast, the archetype *"Medium crop farm"* archetype shows above-average crop production and arable land but only below-average stocking density and milk yield and a larger area of uncultivated agricultural land. Both archetypes show above-average direct payments and total subsidies.

3.2. Regional distribution

In the western federal states in Germany, six archetypes were found in 1992 while fewer archetypes were identified in these regions between 2003 and 2019 (Fig. 3). However, as mentioned above, no data were available for 1992 for the eastern federal states – the former territory of the German Democratic Republic. The lack of data, i.e. different structure of the data space, may partly explain the fewer archetypes found in the western part of Germany between 2003 and 2019.

In 1992, the archetype *"Small dairy farm"* was the most present archetype. The *"Small crop farm"* was also quite frequently represented, especially in Bavaria and Lower Saxony. *"Extensive grazing farm"* was also more common in the western part of Germany in 1992.

In 2003, the *"Small dairy farm"* and *"Small crop farm"* archetypes dominate German grassland systems. While this situation persists in the western federal states in the following years, these two archetypes are less prevalent in the eastern federal states in 2013 and 2019. Overall, the diversity of archetypes is greatest in 2013. In the western federal states, larger shares of the archetypes *"Extensive grazing farm"* and *"Crop farm and uncultivated land"* were found again in 2013. In the eastern federal states, "*Mixed farm*" and "*Medium crop farm*" archetypes emerged. Compared with 2003, a shift is noticeable from the *"Small dairy farm"* archetype to higher shares of the *"Small crop farm"* archetype in 2013 and2019 in Bavaria, Baden-Wuerttemberg and Hesse. In the eastern federal states, the *"Medium crop farm"* archetype becomes more prevalent in 2019 in contrast to other archetypes that include animal husbandry.

4. Discussion

The dynamic archetype analysis revealed a significant trend of agricultural land systems in Germany over time. Five of the nine archetypes were identified in all the years analysed. These are the "*Small crop farm*", "*Small dairy farm*", "*Extensive grazing farm*", "*Small ruminant farm*", and *"Crop farm and uncultivated land"* archetypes, albeit with varying regional shares. The emergence of the *"Large subsidised mixed*

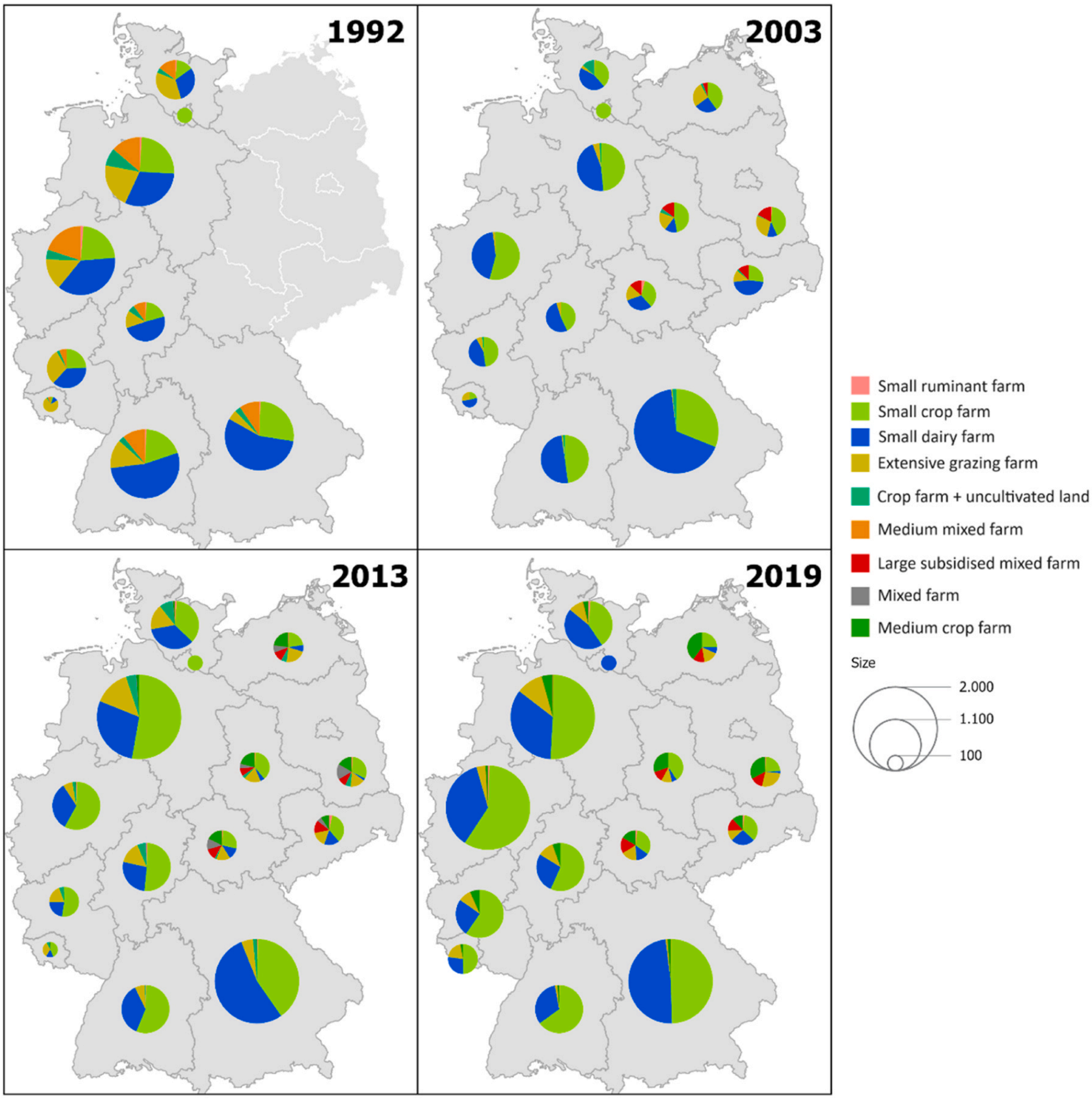

Fig. 3. Distribution of agricultural land system archetypes in 1992, 2003, 2013 and 2019. (Note: due to missing data in 1992 we marked the border between the eastern federal states in white colour).

farm" archetype in 2003 can be interpreted as a result of various subsidies and policies implemented in Germany from 1992 to 2003. These include, among others, the introduction of coupled direct payments for grains and livestock (see Table 1). These encouraged farmers to adopt integrated farming systems that combined crop production, livestock rearing and other diversified activities such as agroforestry and energy production. The emergence of the *"Large subsidised mixed farm"* archetype was also fostered by livestock premiums that incentivised farmers to stabilise livestock production and animal husbandry practices. In the current CAP funding period, which is in effect since January 2023, farmers who receive direct payments are only allowed to convert their grassland under certain conditions. Taking a more rigorous approach, some federal states such as Baden-Wuerttemberg, Mecklenburg-Western Pomerania and Schleswig-Holstein have state laws that generally prohibit the conversion of grasslands (Zinngrebe et al., 2017).

The prevalence of the *"Small crop farm"* and *"Small dairy farm"* archetypes in Bavaria, Lower Saxony and North Rhine-Westphalia can be partly explained by the milk crisis in 2015. Most farms that invested in new stables with borrowed capital went bankrupt (Pieralli et al., 2017). Farms that were able to finance the investments to a large extent from their own capital managed to remain competitive but remained small (Sauer and Latacz-Lohmann, 2015). Farms that did not invest, mostly regionally operating family farms which can be described as atypical dairy farms, felt little impact of the milk crisis (Sauer and Latacz-Lohmann, 2015). Relatively small farms survived better. However, this is counteracted by structural changes (Zimmermann and Heckelei, 2012), which caused small farms to disappear, leaving behind a few large, specialised farms.

A major challenge for grassland conservation arises when a uniformly defined political framework does not meet particular regional dynamics. For example, a specific shift towards a higher share of the *"Small crop farm"* archetype and a decline of *"Small dairy farm"* archetype was found in the federal state of Bavaria between 2013 and 2019. This shift can be attributed to challenging market conditions, increased requirements for animal husbandry, or a lack of successors for small farms. If this trend continues in the coming years, it may lead to a further decrease in extensive pasture systems, particularly concerning alpine farming practices in Bavaria. As these pasture systems entail low inputs of agrochemicals and pesticides as well as low livestock density, they bear great potential for conserving biodiversity and ecosystem services. A particularly high share of species-rich farmland predicted in Bavaria indicates the importance of this region as a priority area for conservation actions (Klimek et al., 2014). The low-input grassland systems prevalent in this region are associated with diverse cultural and natural heritages, known as high nature value (HNV) farmlands (Lomba et al., 2022). Further grassland abandonment implies succession toward bush encroachment and expansion of shrubs and trees associated with the loss of habitats for wild species that depend on extensive land use, such as vascular plants, butterflies and ground beetles. Therefore, there is a need for more targeted political measures, such as the already existing Bavarian agri-environmental climate measures for the management of alpine pastures, which explicitly support the *"Small dairy farm"* archetype in Bavaria and aim to counteract the ongoing abandonment of extensively used grassland.

Moreover, the Nature Restoration Law, recently adopted by EU member states, set the target to increase the share of agricultural land with high-diversity landscape features such as buffer strips, hedgerows, tree rows and field margins (Hering et al., 2023). Regionally specific approaches are needed to achieve this target depending on current farm properties. For example, the *"Medium crop farm"* and *"Large subsidised mixed farm"* archetypes with greater farm size that prevail in the eastern federal states (Fig. 3) may encompass higher heterogeneity at the farm level, including less productive areas. Premium payments for farms that manage grassland in small plots or subdivide large plots would be important as they would provide incentives to use less productive areas to establish high-diversity landscape features without major yield loss. The support of agroecological practices, such as defined in the Kunming-Montreal Global Biodiversity Framework (target 10), would be particularly beneficial to create suitable living conditions for wild species. The "*Small crop farm*" and "*Small dairy farm*" archetypes with a smaller farm size that dominate the western federal states would benefit from collective contracts and implementation schemes. These would be important to foster the creation of biotope networks of high-diversity landscape features at the landscape scale.

The current CAP for 2023–2027 has partially addressed the necessity of focusing on the implementation of specific policy measures in particular regions. To further support the sustainability of farms and preserve important land use systems, the CAP should continue to focus on ensuring profitability for farms while prioritising the maintenance of regionally adapted land use practices. This could involve providing targeted financial incentives for the *"Small dairy farm"* archetype, reducing bureaucratic hurdles for maintaining grazed grasslands and promoting sustainable agricultural practices that enhance biodiversity and ecosystem services. By aligning CAP measures with the needs of diverse farming systems and landscapes, policymakers can contribute to the long-term viability of agriculture while safeguarding valuable land use traditions.

Overall, the year 2013 shows the highest diversity of archetypes, particularly in the eastern federal states, although data limitations in these regions impede comparison in 1992. From the perspective of building resilience in the agricultural sector, one of the key objectives of the current CAP, 2013 indicated the year with the best capacity at a broader national level and particularly in the eastern federal states, to withstand disturbances such as weather extremes and market variability. Resilience describes how much disturbance a system can withstand while maintaining its core structure and functions (Folke, 2006). The greater diversity of archetypes in 2013 implies greater response diversity, i.e. higher variability of ways to deal with disturbances. Hence, the decreased diversity of archetypes in 2019 entails a decline in resilience. Policy measures such as points-based eco-schemes, agri-environmental programs and support for cross-sectoral cooperation are essential to re-enhance resilience in the future. A future CAP which better balances and tailors policy mixes to regional needs and opportunities is vital to halt and reverse biodiversity loss (Sietz et al., 2022), framed as a key CAP objective.

5. Conclusion

In this paper, we showed that nine archetypical patterns determined grassland systems in Germany during 1992–2019. These archetypes were characterised by typical combinations of 16 farm accountancy indicators. Regional dynamics at the level of German federal states involved the emergence, disappearance and persistence of the archetypes. For example, an archetype encompassing mixed farms only appeared in 1992, while a new archetype covering large subsidised mixed farms emerged in 2003 in the eastern federal states and persisted. In 2013, two new archetypes emerged, capturing medium mixed farms and medium crop farms, of which the former did not persist in 2019. Overall, the diversity of archetypes was greatest in 2013, particularly in the eastern federal states.

Enhancing previous archetype studies, this study provides a first methodological approach that combines dynamic archetype analysis with an exploration of policy impacts on the archetype dynamics. It integrates accountancy data at the farm level to identify archetypes, synthesise these at the level of federal states in Germany and discuss CAP effects on changes in archetypes. Building on this discussion, the archetypes offer valuable insights for tailoring policy instruments such as premium payments and agri-environmental climate measures to specific groups of farms and regional conditions. This would help maintain functional grasslands and enhance the resilience of the farming sector more effectively. By enhancing farm diversity at the regional level, policymakers can leverage greater response diversity to better address weather or market disturbances. This approach emphasises the importance of promoting farm diversity within federal states to collectively build resilience at a regional scale, rather than focusing solely on individual farm-level resilience strategies. The insights derived can support the transfer of successful policy instruments across regions based on the similarities shown by the archetypes. This follows the assumption that policy instruments would be successful in comparable grassland situations. This applies to regions in Germany and other grassland regions in Europe. In this context, identifying archetypes of agricultural land systems and their temporal dynamics in other European grassland regions would offer new opportunities to regionally adapt the design of CAP measures.

To further advance policy tailoring and the transfer of policy instruments, future research could replicate the approach presented here in other grassland regions in Europe and worldwide. In doing so, current data collection could be expanded by systematically including environmental and social sustainability indicators. Moreover, analysing archetypes at finer spatial resolutions, such as the municipal level, could reveal further specificities in regional farming dynamics, offering additional information to refine policy decisions. A more detailed investigation of country-specific policies would also support the further fine-tuning of grassland-related policies.

CRediT authorship contribution statement

Richard Orozco: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marie Meyer-Jürshof:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Karla Vergara-Rodríguez:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Tomáš Václavík:** Writing – review & editing, Validation, Software, Methodology. **Diana Sietz:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

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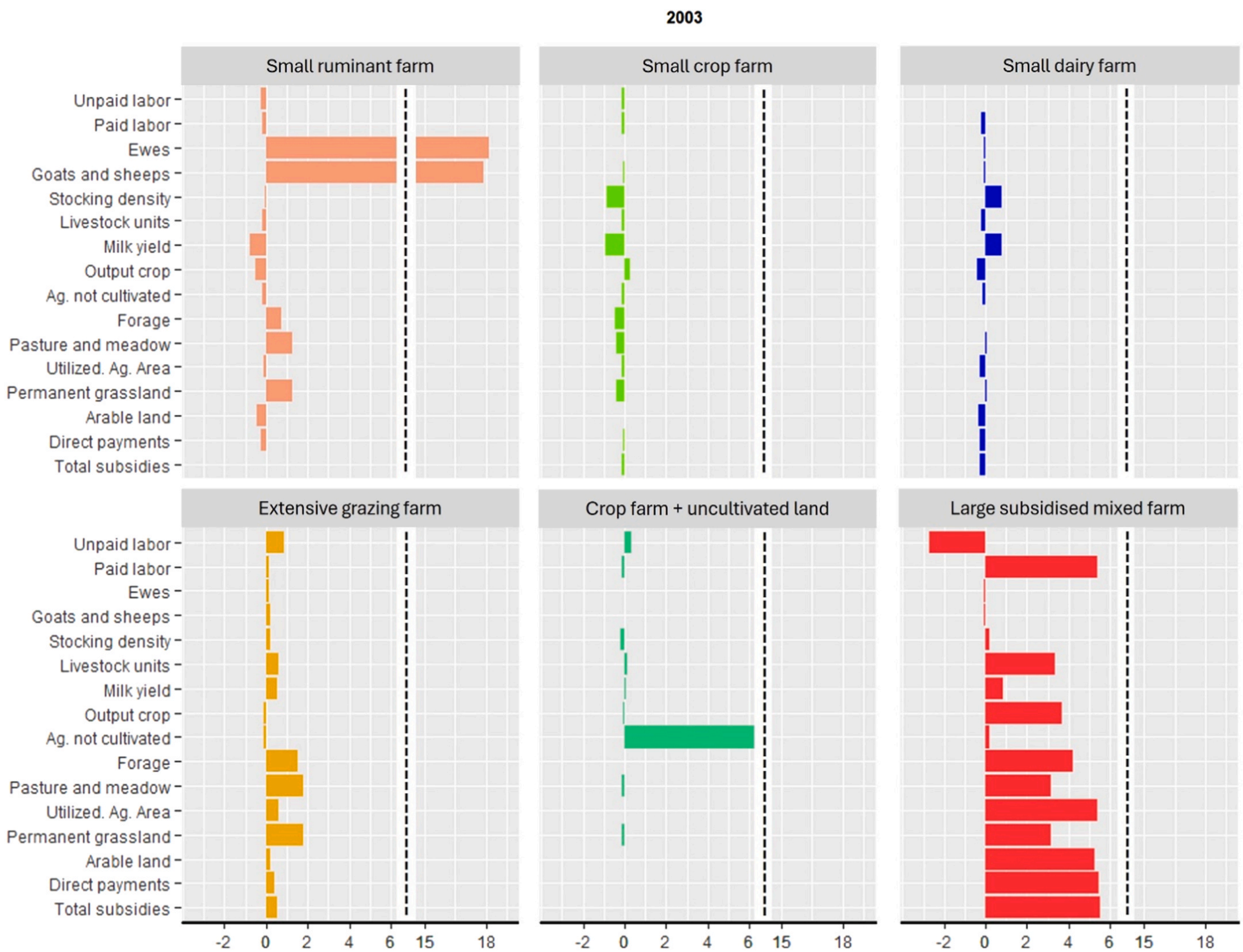
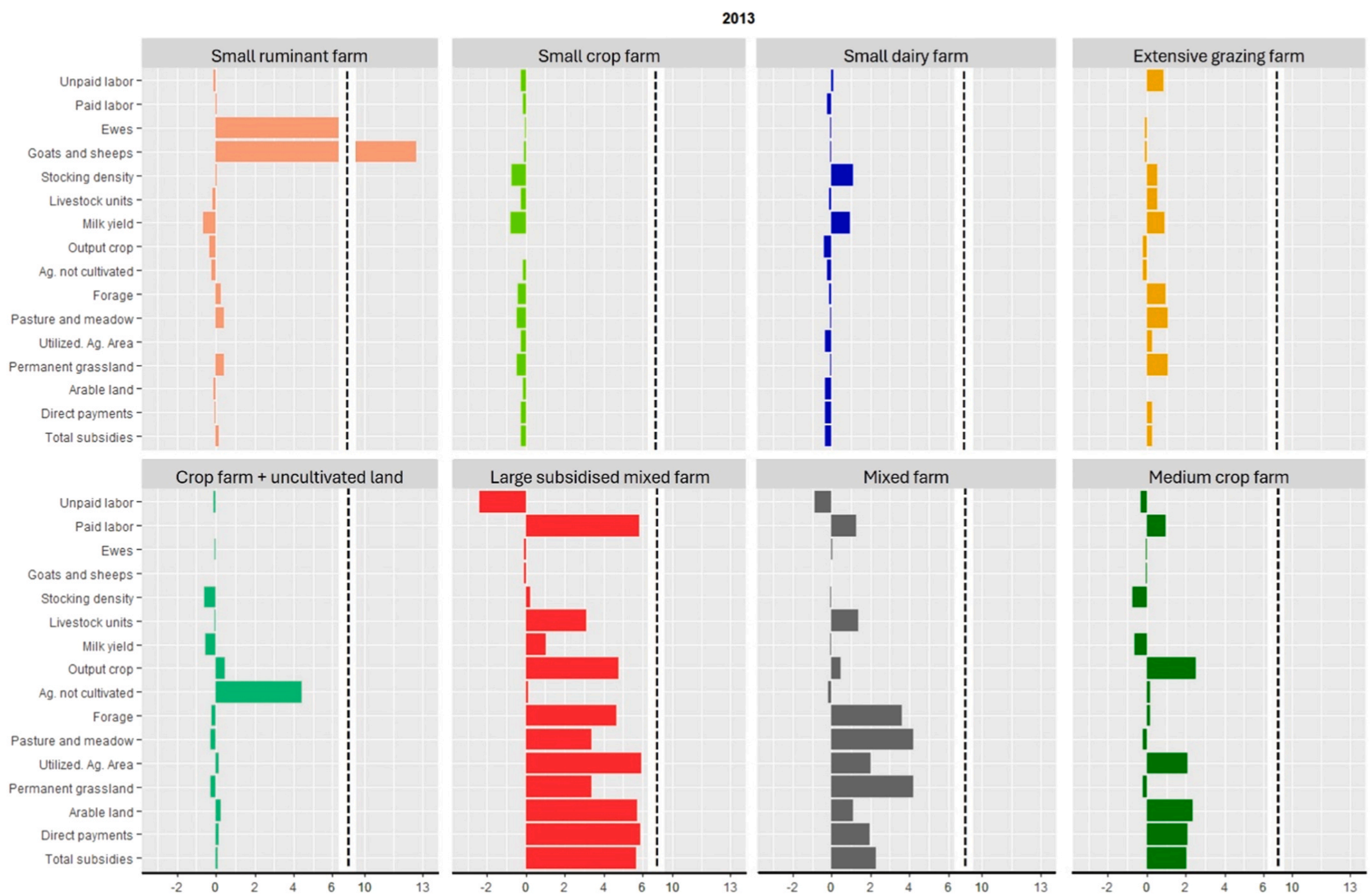
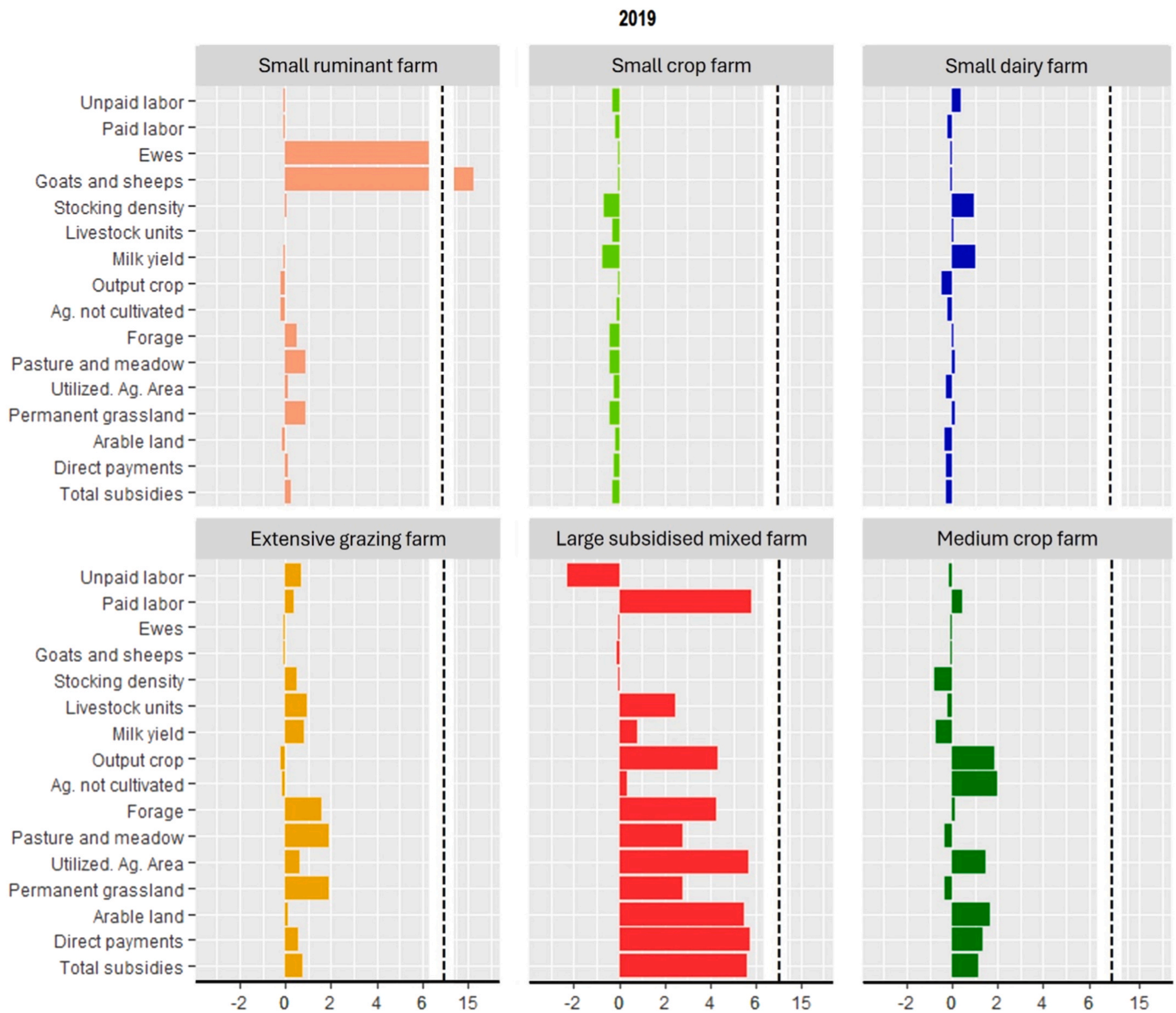
Appendix A. List of Indicators with full description

Indicator	Unit	Description
Unpaid Labour	hours	Time worked in hours by unpaid labour input (generally family) on holding.
Paid Labour Input	hours	Time worked in hours by total labour input on holding.
Ewes, Breeding females	average number	Ewes and breeding females.
Goats, other goats, ewes and sheep	units	Goats, other goats, ewes and other sheep.
Stocking density	unit/ha	Density of ruminant grazing livestock: average number of bovine LU (except calves for fattening) and sheep/goats per hectare of forage UAA. Forage area includes fodder crops, agricultural fallows and land withdrawn from production (not cultivated, except in the exceptional cases of crops under set-aside schemes). Stocking density is calculated only for holdings with corresponding animals and with forage area.
Total livestock units	units	Number of equidae, cattle, sheep, goats, pigs and poultry present on holding in annual average terms, converted into livestock units (LU)5. Not included are beehives, rabbits and other animals. Animals which do not belong to the holder but are held under production contract are taken into account to their annual presence.
Milk yield	kg/cow	Average production of milk and milk products (in milk equivalents) in kg per dairy cow. Production includes farmhouse consumption and farm use (distributed to animals). Holdings without dairy cows are excluded.
Total output crops & crop production (EUR)	EUR	= Sales + farm use + farmhouse consumption + (closing valuation - opening valuation)
Agricultural land not cultivated	ha	Agricultural land not cultivated for agricultural reasons.
Forage	ha	Fodder roots and brassicas (mangolds, etc.), other fodder plants, temporary grass, meadows and permanent pastures, rough grazing.
Pasture and Meadow	ha	Temporary grass, meadows and permanent pastures, rough grazing.
Total utilised agricultural area	ha	Total utilised agricultural area of holding. Does not include areas used for mushrooms, land rented for less than one year, woodland and other farm areas (roads, ponds, non-farmed areas, etc.). It consists of land in owner occupation, rented land for a period of at least one year, land in share-cropping. It includes agricultural land temporarily not under cultivation for agricultural reasons or being withdrawn from production as part of agricultural policy measures. It is expressed in hectares (10,000 m2).
Permanent grassland	ha	Land used to grow grasses or other herbaceous forage naturally (self-seeded) or through cultivation (sown) and that has not been included in the crop rotation of the holding for five years or more. Area of permanent grassland and permanent pasture.
Arable land	ha	Area of land cultivated for crop production or areas available for crop production but lying fallow; does not include mushrooms' area.
Total direct payments	EUR	National decoupled and coupled subsidies, except on rural development, costs and purchase of animals.
Total subsidies	EUR	Total subsidies – excluding on investments.

Appendix B. Bar Plots of 2003, 2013 and 2019




2013
Small ruminant farm
Small crop farm
Small dairy farm
Extensive grazing farm
Crop farm + uncultivated land
Large subsidised mixed farm
Mixed farm
Medium crop farm
Unpaid labor
Paid labor
Ewes
Goats and sheeps
Stocking density
Livestock units
Milk yield
Output crop
Ag. not cultivated
Forage
Pasture and meadow
Utilized. Ag. Area
Permanent grassland
Arable land
Direct payments
Total subsidies
-2
0
2
4
6
10
13



References

Bai, Y., Cotrufo, M.F., 2022. Grassland soil carbon sequestration: current understanding, challenges, and solutions. Science *377* (6606), 603–608. https://doi.org/10.1126/science.abo2380.

Beckmann, M., Didenko, G., Bullock, J.M., Cord, A.F., Paulus, A., Ziv, G., Vaclavik, T., 2022. Archetypes of agri-environmental potential: a multi-scale typology for spatial stratification and upscaling in Europe. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ac9cf5.

Bergmann, D., O'Connor, D., Thümmel, A., 2015. Seasonal and cyclical behaviour of farm gate milk prices. Br. Food J. *117* (12), 2899–2913. https://doi.org/10.1108/BFJ-08-2014-0294.

Bruns, D., Ipsen, D., Bohnet, I., 2000. Landscape dynamics in Germany. Landsc. Urban Plan. *47* (3–4), 143–158. https://doi.org/10.1016/S0169-2046(99)00083-3.

Chang, J., Ciais, P., Gasser, T., Smith, P., Herrero, M., Havlík, P., Obersteiner, M., Guenet, B., Goll, D.S., Li, W., Naipal, V., Peng, S., Qiu, C., Tian, H., Viovy, N., Yue, C., Zhu, D., 2021. Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. Nat. Commun. *12* (1), 118. https://doi.org/10.1038/s41467-020-20406-7.

Daugbjerg, C., 2003. Policy feedback and paradigm shift in EU agricultural policy: the effects of the MacSharry reform on future reform. J. Eur. Public Policy *10* (3), 421–437. https://doi.org/10.1080/1350176032000085388.

Davies, D.L., Bouldin, D.W., 1979. A cluster separation measure. IEEE Trans. Pattern Anal. Mach. Intell. *PAMI-1* (2), 224–227. https://doi.org/10.1109/TPAMI.1979.4766909.

Destatis (2018a). Employees and turnover in the German manufacturing industry from 2008 to 2016. Genesis-Online database of the Federal Office for Statistics, Wiesbaden.

Destatis. (2018b). Exports of German dairy and dairy products from 2008 to 2016.

Destatis. (2022). Bodennutzung der Betriebe—Landwirtschaftlich genutzte Flächen—Fachserie 3 Reihe 3.1.2—2021. Destatis. https://bit.ly/3wzWEKu.

Dittrich, A., Seppelt, R., Václavík, T., Cord, A.F., 2017. Integrating ecosystem service bundles and socio-environmental conditions – a national scale analysis from Germany. Ecosyst. Serv. *28*, 273–282. https://doi.org/10.1016/j.ecoser.2017.08.007.

Dou, Y., Cosentino, F., Malek, Z., Maiorano, L., Thuiller, W., Verburg, P.H., 2021. A new European land systems representation accounting for landscape characteristics. Landsc. Ecol. *36* (8), 2215–2234. https://doi.org/10.1007/s10980-021-01227-5.

Eisenack, K., Oberlack, C., Sietz, D., 2021. Avenues of archetype analysis: roots, achievements, and next steps in sustainability research. Ecol. Soc. *26* (2), art31 https://doi.org/10.5751/ES-12484-260231.

European Commission. (2016). EU agricultural outlook: Prospects for the EU agricultural markets and income 2016-2026 (12/2016). https://ec.europa.eu/agriculture/sites/agriculture/files/markets-and-prices/medium-term-outlook/2016/2016-fullrep_en.pdf.

European Commission. (2019). Russian import ban on agricultural products. https://ec.europa.eu/agriculture/russian-import-ban_fr.
Folke, C., 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. Glob. Environ. Change *16* (3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002.
Hering, D., Schürings, C., Wenskus, F., Blackstock, K., Borja, A., Birk, S., Bullock, C., Carvalho, L., Dagher-Kharrat, M.B., Lakner, S., Lovrić, N., McGuinness, S., Nabuurs, G.-J., Sánchez-Arcilla, A., Settele, J., Pe'er, G., 2023. Securing success for the NAture Restoration Law. Science *382* (6676), 1248–1250. https://doi.org/10.1126/science.adk1658.
Hussain, R.I., Walcher, R., Eder, R., Allex, B., Wallner, P., Hutter, H.-P., Bauer, N., Arnberger, A., Zaller, J.G., Frank, T., 2019. Management of mountainous meadows associated with biodiversity attributes, perceived health benefits and cultural ecosystem services. Sci. Rep. *9* (1), 14977 https://doi.org/10.1038/s41598-019-51571-5.
Jongeneel, R., Gonzalez-Martinez, A.R., 2022. The role of market drivers in explaining the EU milk supply after the milk quota abolition. Econ. Anal. Policy *73*, 194–209. https://doi.org/10.1016/j.eap.2021.11.020.
Kerckow, B., 1993. Die Landwirtschaftlichen Märkte 1992 93. Der Markt F. üR. Milch und Fette. https://doi.org/10.22004/AG.ECON.301380.
Klimek, S., Lohss, G., Gabriel, D., 2014. Modelling the spatial distribution of species-rich farmland to identify priority areas for conservation actions. Biol. Conserv. *174*, 65–74. https://doi.org/10.1016/j.biocon.2014.03.019.
Lakner, S., Holst, C., 2015. Betriebliche umsetzung der greening-Auflagen: die ökonomischen bestimmungsgründe. Nat. Und Landsch. *90* (6), 271–277.
Levers, C., Müller, D., Erb, K., Haberl, H., Jepsen, M.R., Metzger, M.J., Meyfroidt, P., Plieninger, T., Plutzar, C., Stürck, J., Verburg, P.H., Verkerk, P.J., Kuemmerle, T., 2018. Archetypical patterns and trajectories of land systems in Europe. Reg. Environ. Change *18* (3), 715–732. https://doi.org/10.1007/s10113-015-0907-x.
Locatelli, B., Lavorel, S., Sloan, S., Tappeiner, U., Geneletti, D., 2017. Characteristic trajectories of ecosystem services in mountains. Front. Ecol. Environ. *15* (3), 150–159. https://doi.org/10.1002/fee.1470.
Lomba, A., Ferreiro Da Costa, J., Ramil-Rego, P., Corbelle-Rico, E., 2022. Assessing the link between farming systems and biodiversity in agricultural landscapes: insights from Galicia (Spain). J. Environ. Manag. *317*, 115335 https://doi.org/10.1016/j.jenvman.2022.115335.
Lüdeke, M.K.B., C. Walther, T. Sterzel, M. Kok, P. Lucas, P. Janssen, and H. Hilderink (2014). Understanding change in patterns of vulnerability. PIK-Report 127, Potsdam Institute for Climate Impact Research.
Martin, A.E., Collins, S.J., Crowe, S., Girard, J., Naujokaitis-Lewis, I., Smith, A.C., Lindsay, K., Mitchell, S., Fahrig, L., 2020. Effects of farmland heterogeneity on biodiversity are similar to—Or even larger than—The effects of farming practices. Agric. Ecosyst. Environ. *288*, 106698 https://doi.org/10.1016/j.agee.2019.106698.
Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., DeFries, R.S., Dyer, G.A., Gibbs, H.K., Lambin, E.F., Morton, D.C., Robiglio, V., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. Environ. Res. Lett. *9* (7), 074012 https://doi.org/10.1088/1748-9326/9/7/074012.
Neuenfeldt, S., & Gocht, A. (2012). A Handbook on the use of FADN Database in Programming Models. Thünen-Institut für Ländliche Räume. https://literatur.thuenen.de/digbib_extern/dn054328.pdf.
Neyret, M., Fischer, M., Allan, E., Hölzel, N., Klaus, V.H., Kleinebecker, T., Krauss, J., Le Provost, G., Peter, S., Schenk, N., Simons, N.K., Van Der Plas, F., Binkenstein, J., Börschig, C., Jung, K., Prati, D., Schäfer, D., Schäfer, M., Schöning, I., Manning, P., 2021. Assessing the impact of grassland management on landscape multifunctionality. Ecosyst. Serv. *52*, 101366 https://doi.org/10.1016/j.ecoser.2021.101366.
Oberlack, C., Pedde, S., Piemontese, L., Václavík, T., Sietz, D., 2023. Archetypes in support of tailoring land-use policies. Environ. Res. Lett. *18* (6), 060202 https://doi.org/10.1088/1748-9326/acd802.
Oberlack, C., Sietz, D., Bürgi Bonanomi, E., de Bremond, A., Dell'Angelo, J., Eisenack, K., Ellis, E.C., Epstein, G., Giger, M., Heinimann, A., Kimmich, C., Kok, M.T., Manuel-Navarrete, D., Messerli, P., Meyfroidt, P., Václavík, T., Villamayor-Tomas, S., 2019. Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. Ecol. Soc. *24* (2), art26 https://doi.org/10.5751/ES-10747-240226.
Orozco, R., Grundmann, P., 2022. Readiness for innovation of emerging grass-based businesses. J. Open Innov. Technol. Mark. Complex. *8* (4), 180 https://doi.org/10.3390/joitmc8040180.
Orozco, R., Mosquera-Losada, M.R., Rodriguez, J., Adamseged, M.E., & Grundmann, P. (2021). Supportive Business Environments to Develop Grass Bioeconomy in Europe. https://doi.org/10.3390/su132212629 (registering DOI).
Pe'er, G., Finn, J.A., Díaz, M., Birkenstock, M., Lakner, S., Röder, N., Kazakova, Y., Šumrada, T., Bezák, P., Concepción, E.D., Dänhardt, J., Morales, M.B., Rac, I., Špulerová, J., Schindler, S., Stavrinides, M., Targetti, S., Viaggi, D., Vogiatzakis, I.N., Guyomard, H., 2022. How can the European common agricultural policy help halt biodiversity loss? Recommendations by over 300 experts. Conserv. Lett. *15* (6) https://doi.org/10.1111/conl.12901.
Pieralli, S., Hüttel, S., Odening, M., 2017. Abandonment of milk production under uncertainty and inefficiency: the case of western German Farms. Eur. Rev. Agric. Econ. *44* (3), 425–454. https://doi.org/10.1093/erae/jbx001.
Santos, J.L., Moreira, F., Ribeiro, P.F., Canadas, M.J., Novais, A., Lomba, A., 2021. A farming systems approach to linking agricultural policies with biodiversity and ecosystem services. Front. Ecol. Environ. *19* (3), 168–175. https://doi.org/10.1002/fee.2292.
Sauer, J., Latacz-Lohmann, U., 2015. Investment, technical change and efficiency: empirical evidence from German dairy production. Eur. Rev. Agric. Econ. *42* (1), 151–175. https://doi.org/10.1093/erae/jbu015.
Schils, R.L.M., Bufe, C., Rhymer, C.M., Francksen, R.M., Klaus, V.H., Abdalla, M., Milazzo, F., Lellei-Kovács, E., Berge, H. ten, Bertora, C., Chodkiewicz, A., Dămătîrcă, C., Feigenwinter, I., Fernández-Rebollo, P., Ghiasi, S., Hejduk, S., Hiron, M., Janicka, M., Pellaton, R., Price, J.P.N., 2022. Permanent grasslands in Europe: land use change and intensification decrease their multifunctionality. Agric. Ecosyst. Environ. *330*, 107891 https://doi.org/10.1016/j.agee.2022.107891.
Sietz, D., Frey, U., Roggero, M., Gong, Y., Magliocca, N., Tan, R., Janssen, P., Václavík, T., 2019. Archetype analysis in sustainability research: methodological portfolio and analytical frontiers. Ecol. Soc. https://doi.org/10.5751/ES-11103-240334.
Sietz, D., Klimek, S., Dauber, J., 2022. Tailored pathways toward revived farmland biodiversity can inspire agroecological action and policy to transform agriculture. Commun. Earth Environ. *3* (1), 211. https://doi.org/10.1038/s43247-022-00527-1.
Sietz, D., Mamani Choque, S.E., Lüdeke, M.K.B., 2012. Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. Reg. Environ. Change *12* (3), 489–505. https://doi.org/10.1007/s10113-011-0246-5.
Sietz, D., Ordoñez, J.C., Kok, M.T.J., Janssen, P., Hilderink, H.B.M., Tittonell, P., Van Dijk, H., 2017. Nested archetypes of vulnerability in African drylands: where lies potential for sustainable agricultural intensification? Environ. Res. Lett. *12* (9), 095006 https://doi.org/10.1088/1748-9326/aa768b.
Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agric. Syst. *98* (3), 208–219. https://doi.org/10.1016/j.agsy.2008.07.004.
Sodano, V., Gorgitano, M.T., 2021. Understanding the role of the common agricultural policy in achieving sustainability and rural development goals. AGROFOR *6* (2). https://doi.org/10.7251/AGRENG2102090S.
Swinnen, J.F.M., & Centre for European Policy Studies (Eds.). (2008). The perfect storm: The political economy of the Fischler reforms of the Common Agricultural Policy. Centre for European Policy Studies.
Tittonell, P., Bruzzone, O., Solano-Hernández, A., López-Ridaura, S., Easdale, M.H., 2020. Functional farm household typologies through archetypal responses to disturbances. Agric. Syst. *178*, 102714 https://doi.org/10.1016/j.agsy.2019.102714.
Turner, B.L., Wuellner, M., Nichols, T., Gates, R., Tedeschi, L.O., Dunn, B.H., 2017. A systems approach to forecast agricultural land transformation and soil environmental risk from economic, policy, and cultural scenarios in the north central United States (2012–2062). Int. J. Agric. Sustain. *15* (2), 102–123. https://doi.org/10.1080/14735903.2017.1288029.
Vaclavik, T., Beckmann, M., Bednář, M., Brdar, S., Breckenridge, G., Cord, A.F., Domingo-Marimon, C., Gosal, A., Langerwisch, F., Paulus, A., Roilo, S., Šarapatka, B., Ziv, G., Čejka, T., 2024. Farming system archetypes help explain the uptake of agri-environment practices in Europe. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ad4efa.
Vidal Merino, M., Sietz, D., Jost, F., Berger, U., 2019. Archetypes of climate vulnerability: a mixed-method approach applied in the peruvian andes. Clim. Dev. *11* (5), 418–434. https://doi.org/10.1080/17565529.2018.1442804.
Vogt, J., Klaus, V., Both, S., Fürstenau, C., Gockel, S., Gossner, M., Heinze, J., Hemp, A., Hölzel, N., Jung, K., Kleinebecker, T., Lauterbach, R., Lorenzen, K., Ostrowski, A., Otto, N., Prati, D., Renner, S., Schumacher, U., Seibold, S., Weisser, W., 2019. Eleven years' data of grassland management in Germany. e36387 Biodivers. Data J. *7*. https://doi.org/10.3897/BDJ.7.e36387.
Wehrens, R., Kruisselbrink, J., 2018. Flexible self-organizing maps in kohonen 3.0. J. Stat. Softw. *87* (7) https://doi.org/10.18637/jss.v087.i07.
Wolff, S., Hüttel, S., Nendel, C., Lakes, T., 2021. Agricultural landscapes in brandenburg, Germany: an analysis of characteristics and spatial patterns. Int. J. Environ. Res. *15* (3), 487–507. https://doi.org/10.1007/s41742-021-00328-y.
Zarbá, L., Piquer-Rodríguez, M., Boillat, S., Levers, C., Gasparri, I., Aide, T.M., Álvarez-Berríos, N.L., Anderson, L.O., Araoz, E., Arima, E., Batistella, M., Calderón-Loor, M., Echeverría, C., Gonzalez-Roglich, M., Jobbágy, E.G., Mathez-Stiefel, S.-L., Ramirez-Reyes, C., Pacheco, A., Vallejos, M., Grau, R., 2022. Mapping and characterizing social-ecological land systems of South America. art27 Ecol. Soc. *27* (2). https://doi.org/10.5751/ES-13066-270227.
Zimmermann, A., Heckelei, T., 2012. Structural change of european dairy farms – a cross-regional analysis. J. Agric. Econ. *63* (3), 576–603. https://doi.org/10.1111/j.1477-9552.2012.00355.x.
Zinngrebe, Y., Pe'er, G., Schueler, S., Schmitt, J., Schmidt, J., Lakner, S., 2017. The EU's ecological focus areas – how experts explain farmers' choices in Germany. Land Use Policy *65*, 93–108. https://doi.org/10.1016/j.landusepol.2017.03.027.