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Semi-natural grassland abandonment in relation to agricultural land management under Common Agricultural Policy in boreonemoral Europe

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Abstract. The Common Agricultural Policy (CAP) has had a major impact on agricultural land use changes in Europe. While grassland abandonment in mountain areas is well-documented, there is a gap in research regarding lowland regions. We investigated how changes in CAP regulations between two periods (2007–2013 and 2014–2020) influenced the pattern of semi-natural grassland (SNG) abandonment in boreonemoral Europe. We used 25 km^2 grid cells as the basic research unit. The relationship between agricultural land management variables and SNG abandonment was analyzed by regression methodology and non-linear relationships were detected. We observed a decrease in the overall rate of SNG abandonment during the second CAP period (2014–2020), suggesting that recent CAP modifications have had some positive impact on grassland conservation. However, the impact of CAP on SNG abandonment varied between the two regions differing in land capability for agriculture and between productive and unproductive SNG types. The study highlights the importance of understanding the complex processes that influence abandonment in strongly non-linear ways. It underscores the importance of tailored conservation strategies and the role of the CAP in shaping SNG management practices.

Key words: agri-environment, CAP support, grassland loss, Habitats Directive, intensification, land capability for agriculture.

Used abbreviations. AES agri-environmental scheme, LCA land capability for agriculture, PG permanent grassland, SNG semi-natural grassland.

INRODUCTION

Semi-natural permanent grasslands (SNG) are among the most valuable ecosystems for biodiversity conservation in agricultural landscapes in the European Union, with most of them being habitats listed in Annex I of Directive 92/43/EEC (Bengtsson et al., 2019; Herzon et al., 2022; Prangel et al., 2023). However, starting from the mid-20th century, considerable areas of SNG have been abandoned or converted into arable land or improved grassland (Pe'er et al., 2014). Particularly high risks of agricultural intensification have been shown for the Baltic States in boreonemoral Europe (European Commission, 2019). At the same time, the risk of agricultural land abandonment is also rated as one of the highest in the Baltics (Terres et al., 2015).

While a bulk of literature examines grassland abandonment in mountain areas (due to the dominance of this agricultural land management type) (MacDonald et al., 2000; Gellrich et al., 2007; Hinojosa et al., 2016; Argenti, et al., 2020; Dax et al., 2021), there are surprisingly few studies exploring the driving factors of grassland abandonment in lowland regions (Biro et al., 2013). This could be related to the fact that grassland loss in lowland areas is more linked to their conversion to croplands and to a much lesser extent to abandonment (Wittig et al., 2010; Ridding et al., 2015). In addition, the majority of agricultural land abandonment studies do not distinguish between arable land and grassland, assuming the same driving factors for both land management types (Pazúr et al., 2014; Terres et al., 2015; Filho et al., 2016; Ustaoglu & Collier, 2018).

However, in boreonemoral Europe, mixed land-use agricultural landscapes at a farm level were common until the mid-20th c. The common practice was to have grasslands only on soils that were the least suitable for agricultural use. Thus, abandonment affected grasslands more than arable land in the mid-20th c. (Penēze et al. 2009; Aune et al., 2018; Rūsiņa et al., 2021). From the mid-20th century, the largest abandonment has been induced by the Common Agricultural Policy (CAP) in Western European countries and by the fall of the communist regime in Central and Eastern European countries (Biro et al., 2013; Pazúr et al., 2014; Lasanta et al., 2017). In latter, the overall rate of agricultural land abandonment declined after EU accession but it still continued in the more marginal areas where also the share of grasslands was historically higher (Nikodemus et al., 2005; Vanwambeke et al., 2012; Jepsen et al., 2015). CAP rules are therefore one of the main socio-economic factors behind the abandonment of agricultural land.

Socio-economic drivers of the decline in the area of SNG in boreal Europe (including the boreonemoral ecotone) are summarized by Herzon et al. (2022) in a conceptual model of a socio-ecological extinction vortex. The authors identify four highly interlinked and mutually reinforcing socio-economic processes: (1) receding importance for agricultural production, (2) diminishing attention in policy, research, and development; (3) disappearance of the topic in vocational education in the fields of agricultural sciences; and (4) decaying experience of the public.

We were particularly interested in the manifestation of the second process on the pattern of abandonment of SNG. In post-socialist countries, diminished attention to SNG in policy, research, and development that detached SNG from other agricultural land uses was strong until accession to the European Union (Sutcliffe et al., 2015; Herzon et al., 2021). After accession to the EU, agri-environment schemes became available and started to function as the main tool to conserve SNG biodiversity (King, 2010). Thus, attention to SNG in policy has been increasing in the past decades. There is evidence for both positive and negative changes in permanent grassland conservation due to CAP regulations. For example, in Germany, a special legal grassland status reduced grassland conversions to other land-use types and lowered the share of permanent grassland converted to cropland (Haensel et al., 2023). On the other hand, Bulgaria experienced a dramatic loss of permanent grasslands between 2006 and 2010 caused by the intensification of agriculture fostered by CAP (Dobrev et al., 2014). In Slovenia, only

3% of high nature value grasslands were reached by the agri-environmental support, which did not reverse the abandonment (Kaligarič et al., 2019). The contrasting outcomes of CAP illustrate the complexity of policy effects which can be evident even within a single policy measure. For instance, attempts to encourage more active farming through restrictions on the eligibility of certain maintenance practices (e.g. grazing instead of cutting) may result in abandonment of permanent grasslands due to higher expenses for some farmers (Viira et al., 2020). Again, most studies on SNG in relation to CAP have focused on managed grasslands or the loss of SNG due to intensification, but the emphasis on abandonment is almost lacking.

Our study addressed this knowledge gap by focusing on the relationships between SNG abandonment and agricultural land management under CAP in Latvia. We aimed to investigate how alterations in CAP regulations for grassland management between two periods (2007–2013 and 2014–2020) influenced the landscape-scale pattern of SNG abandonment. We hypothesized that the increased focus on grassland conservation in the CAP from 2007–2013 to 2014–2020 would result in a reduction of SNG abandonment, reflected in the altered response of abandonment rates to the landscape-scale pattern of agricultural land management.

Latvia is a suitable example to demonstrate relationships between agricultural land management and abandonment of SNG in boreonemoral Europe since it lies in the central part of the boreonemoral ecotone in Europe (Breckle, 2002) and the share of the area of SNG and other grassland types is comparable with neighbouring countries (Herzon et al. 2021). Joining the EU in 2004 accelerated the intensification of agriculture (Jepsen et al., 2015). During 2010–2016, the number of small (< 30 ha) farms declined by 15.5%, while the number of large (> 200 ha) farms increased by +12.7%. Similarly, the area of meadows and pastures declined from 651,100 ha in 2010 to 631,900 ha in 2020, while the proportion of arable land increased (Agriculture in Latvia, 2017; Agriculture in Latvia, 2020, Auzins et al., 2023). The amount of fertilizer and plant protection products per hectare increased by 10 to 40%, and in some regions, it increased by over 40% between 2012/13 and 2015/16 (European Commission, 2019).

MATERIALS AND METHODS

Study area

Latvia is a lowland country located on the eastern coast of the Baltic Sea in the boreonemoral ecotone of the Northern needle-leaved and Central European broad-leaved forest biome. The mean annual temperature is 6.2 °C, and the precipitation is 650 mm. The vegetation period lasts for 180–200 days. Forests cover ca. 50%, mires cover ca. 6% and agricultural land covers ca. 38%, while semi-natural grasslands occupy less than 1% of the country (Nikodemus et al., 2018). According to the national-level agricultural land classification (Boruks, 2004), the country is divided into five regions according to land capability for agriculture (LCA) (Fig. 1). These regions highly correspond to the intensity of agriculture characterized by the number of households and area of intensive (cereal fields) and extensive (grasslands) agricultural land (Table 1) at the beginning of our study period. Thus, we selected two areas to compare - the region LCA-High included Region 1 (high land capability for agriculture) and Region 2 (land capability for agriculture above intermediate), while the region LCA-Low corresponded to the borders of the

Region 4 (low land capability for agriculture). Regions 1 and 2 are considered to have lower risk of abandonment of utilized agricultural land (UAA) than Region 4 (Perpiña Castillo et al., 2021).

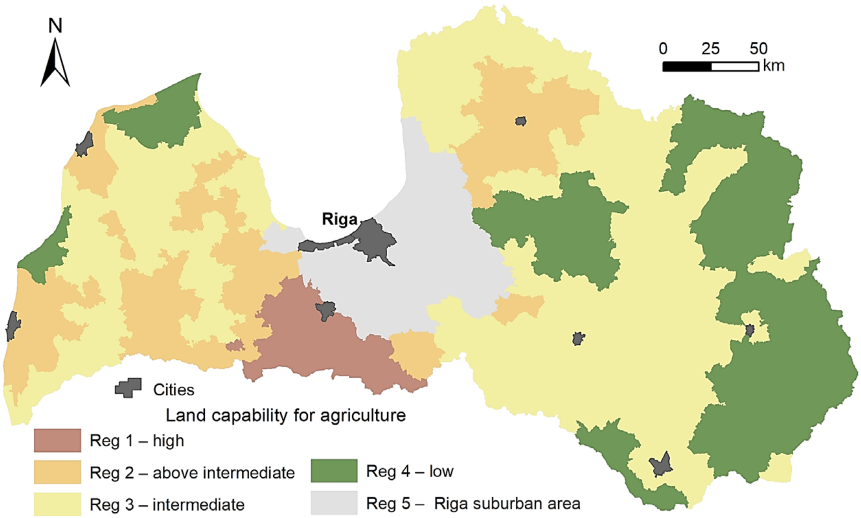

Figure 1. Regions by LCA (Boruks, 2004).

Table 1. Characteristics of five LCA regions as of 2014 (Integrated Administration and Control System data for 2014 from the Rural Support Service)

Region	Number of house-holds per 1,000 ha SAP*	SAP*, ha per 1,000 ha land	Cereal fields, ha per 1,000 ha SAP	Permanent grassl., ha per 1,000 ha SAP	Land capability for agriculture
Reg 1	20	625	637	20	High: fertile loam and clay soils; plain terrain
Reg 2	30	316	457	150	Above intermediate: sandy loam and loam soils; plain and undulating terrain
Reg 3	45	242	323	300	Intermediate: sandy loam and loam soils; undulating and hilly terrain
Reg 4	68	207	205	549	Low: sandy to clay soils; hilly terrain
Reg 5	42	166	302	258	Riga suburban area (intermediate-low): sandy and sandy loam soils; plain to undulating terrain; agricultural constraints mainly socioeconomic, related to active urbanization processes

* SAP – Single Area Payment.

Our data covered the implementation periods of the Rural Development Programme 2007–2013 and 2014–2020. During the first period, SNG conservation management was addressed by the action-oriented agri-environment scheme 'Maintenance of Biodiversity in Grasslands,' aimed at fostering biodiversity-friendly management of SNG across the country. The amount of financial support was 123 EUR per hectare. Eligible areas included all SNG. The management requirements were common for all eligible habitat types and included mowing with or without hay removal once per season from 1 August until 15 September or grazing (0.4–0.9 animal units), and any improvement of grassland was forbidden. Permanent grasslands that were not eligible for the agri-environment scheme could receive a single area payment (direct area-based payments) with the condition that grasslands were cut at least once per season with or without hay removal. No other restrictions were in place.

The same AES continued for SNG in CAP 2014–2020 but with some changes. Concerning management prescriptions, two important changes were introduced. Firstly, the late mowing date (1 August) was cancelled due to farmers' complaints that it significantly reduced the chances of harvesting hay due to bad weather. Secondly, mulching or mowing without hay removal was forbidden, and grass cuttings were required to be removed from the field by 15 September. It should be noted that the same requirement was also imposed on permanent grasslands for single area payments. In addition, the payment calculation for AES changed. Starting in 2015, differentiation of the payment into three classes based on grassland productivity was introduced (83–155 EUR for productive grasslands and 206 EUR for unproductive grasslands). Finally, 'greening' measures were introduced.

To summarize, the important CAP modifications in relation to potential changes in trajectories of SNG abandonment between the two periods in Latvia were (1) introduction of a ban to convert environmentally sensitive permanent grasslands into arable land (in Latvia they included all SNG types across the country); (2) maintenance of the ratio of permanent grassland to agricultural land with a 5% margin of flexibility at national level without precise spatial mapping; (3) substantial increase in the financial support for unproductive SNG and partial decrease for productive grasslands; (4) more flexibility in choosing the mowing date but the option for grass mulching was cancelled.

Data on SNG distribution and productivity

We divided the country into 2,778 grid cells of 25 km^2 and used these cells as the basic landscape-scale unit of research. We analyzed seven SNG habitat types occurring in Latvia. They were split into two groups of productivity according to the habitat-specific national data on productivity (Rūsiņa, 2017). Productive SNG (dry hay more than 1 t ha^{-1} yr^{-1}) included Habitats Directive habitat types (European Commission, 2013; Auniņš, 2013) 6270* (asterix denotes priority habitats), 6450, and 6510, while unproductive SNG (dry hay less than 1 t ha^{-1} yr^{-1}) included 6120*, 6210*, 6230* (see Rūsiņa et al., 2023 for details). We collected data on SNG area and distribution from georeferenced EU grassland habitat maps maintained by the Nature Conservation Agency at the national level. For our first study period, we utilized all polygons mapped between 2001 and 2012, while for the second study period, we used data from 2013 to 2021. It's important to note that we included all polygons in our analysis, regardless of their management status (whether they were managed or abandoned) at the time of mapping.

Data on agricultural land management

Data on agricultural land management were obtained from different sources (Table 2). There are different approaches to define abandonment ranging from detailed use of vegetation parameters, like functional traits (Targetti et al., 2018) to simple… To analyze the state of grassland management, we defined the following management status: (1) abandoned - SNG polygons not included in the agricultural parcel register of the Rural Support Centre and did not receive any payments from CAP instruments; (2) grasslands managed in AES – permanent grassland (PG) polygons (incl. SNG) that received subsidies under the action-oriented agri-environment scheme 'Maintenance of Biodiversity in Grasslands'. All polygons registered in the agricultural parcel register of the Rural Support Centre as arable land were omitted from the analysis.

Table 2. Description of data categories collected per grid cell, their type, and data sources

Data category	Data type	Data source
Area of abandoned semi-natural grasslands (SNG) (response variable)	Continuous; area (ha) per grid cell	SNG parcels not registered in Integrated Administration and Control System of Rural Support Service.
Area of SNG, total	Continuous; total area (ha) of SNG per grid cell	Nature Conservation Agency. Each polygon mapped only once and no update of the fate of the polygon during the two study periods.
Area of permanent grasslands (PG) managed under AES	Continuous; area (ha) per grid cell.	Integrated Administration and Control System of Rural Support Service.
Area of managed PG	Continuous; area (ha) per grid cell	Integrated Administration and Control System of Rural Support Service.
Agricultural land under organic farming	Continuous; area (ha) per grid cell	Integrated Administration and Control System of Rural Support Service.
Arable land area	Continuous; area (ha) per grid cell	Integrated Administration and Control System of Rural Support Service.
Land capability for agriculture (Land quality)	Categorical, 3-point scale (low, medium and high quality). Weighted average per grid cell calculated from all parcels of agricultural land per grid cell	Digitized land quality maps 1: 10,000 from 1960s to 1980s; https://geolatvija.lv/geo/p/317.

To examine the relationships between SNG abandonment and a landscape-scale agricultural land management patterns, we selected a set of explanatory variables that align with our study's objectives, as informed by previous research (Table 2). Previous studies have shown that land capability for agriculture and the total area of arable land tend to have a positive correlation with agricultural land management intensity (Latruffe & Piet, 2014; Vinogradovs, 2018) and grassland loss (Hatna & Bakker, 2011; Biro et al., 2013), while exhibiting a negative association with the preservation of high nature value agricultural lands (Stoate et al., 2009; Reif & Hanzelka, 2016). Additionally, research indicates that the proportion of permanent grasslands under agricultural management and the extent of agricultural land under organic farming have the potential to positively impact agricultural biodiversity (Hole et al., 2005).

Statistical analysis

Our analysis was conducted at the landscape scale, utilizing a study unit consisting of 5 km × 5 km (2,500 ha) grid cells, with a total of 2,778 cells (Krampis, 2012). To ensure the robustness of our findings, all variables underwent testing for spatial autocorrelation using Moran's I statistic (Anselin, 2002). The response variable, which represents the area of abandoned SNG, followed a Tweedie distribution due to its positive continuous nature and a high proportion of zero values. To prepare for modeling, we conducted a test for multicollinearity among the explanatory variables using a Spearman's correlation matrix. Multicollinearity occurs when explanatory variables are highly correlated, violating the assumption of independence. In such cases, it's advisable to retain only one variable from a group of highly correlated ones (Millington et al., 2007). We applied a correlation limit of $R > |0.8|$, but no explanatory variables displayed high correlations with each other, so all were retained in the models.

Upon visually inspecting the relationships between the response variable and each explanatory variable using scatter plots with a LOESS curve, we observed non-linear relationships. Consequently, we opted for generalized additive modeling (GAM) as our modeling approach (Wood, 2017). GAM is an extension of generalized linear models that offers greater flexibility by accommodating non-linear relationships between predictors and the response variable. Rather than assuming a linear relationship, GAM allows for the fitting of smooth, non-linear functions to individual predictors. This approach enables the visualization and understanding of each predictor's effect, and the amount of smoothing for each predictor is typically determined automatically by the model, helping to prevent overfitting.

Eight models were created for this study. Four of these models aimed to uncover relationships between the abandonment of productive SNG and the type of agricultural land management, focusing on two CAP periods (2014 and 2021) and two regions characterized by differing land capability for agriculture (LCA-High and LCA-Low). The remaining four models were developed for the same CAP periods and regions but focused on unproductive SNG. To capture non-linear relationships and make them more interpretable, smooth splines were employed with a constraint of 3 degrees of freedom. Model fit was assessed using the 'gam.check' function, and degrees of freedom were adjusted for variables exhibiting non-randomly distributed residuals, followed by model re-fitting. The stepwise regression technique, guided by Akaike's information criterion (AIC), was used to select the best-fitting model. In order to investigate whether the models adhered to their assumptions, residual analysis was conducted, and diagnostic plots were examined. All calculations and analyses were performed using the R 4.3.1 software package 'mgcv' (Wood, 2017).

RESULTS

Descriptive statistics

In 2014, abandoned SNG covered 20,336 ha, accounting for 39.7% of the total SNG area, and in 2021, they amounted to 17,761 ha, representing 27.9% of the total SNG area. The distribution of abandoned SNG was uneven (see Fig. 2).

The structure of agricultural land management in the two examined regions, LCA-High and LCA-Low, exhibited significant variation, particularly in the ratio of arable land to permanent grasslands (see Fig. 3). Over the two CAP periods, both regions underwent changes in their agricultural land composition. In the LCA-High region, arable land increased by 9%, while in the LCA-Low region, it saw a more significant increase of 18%. In contrast, permanent grasslands expanded by 6% in the LCA-High region but decreased by 2% in the LCA-Low region. These alterations in land use predominantly occurred within sown grasslands (temporary grasslands), which experienced reductions in both regions.

In 2014, the LCA-High region had 2,114 ha of abandoned productive SNG and 1,870 ha of abandoned unproductive SNG. In 2021, the abandoned area was 865 ha and 1,051 ha, respectively. In the LCA-Low region, there were 3,164 ha of abandoned productive SNG and 2,965 ha of abandoned unproductive SNG in 2014. However, by 2021, these numbers changed to 396 ha and 1,203 ha, respectively.

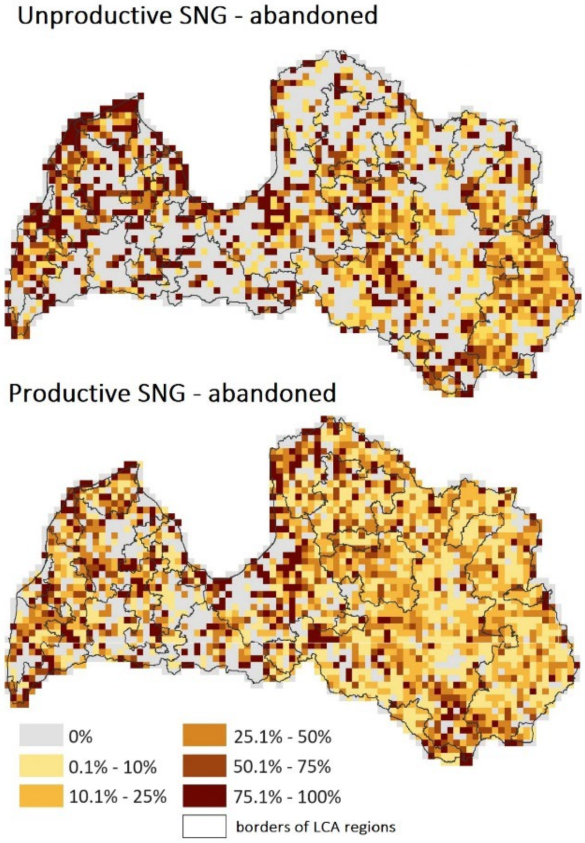

Figure 2. Share of abandoned SNG in Latvia in 2021 as a percentage of the total area of SNG per grid cell.

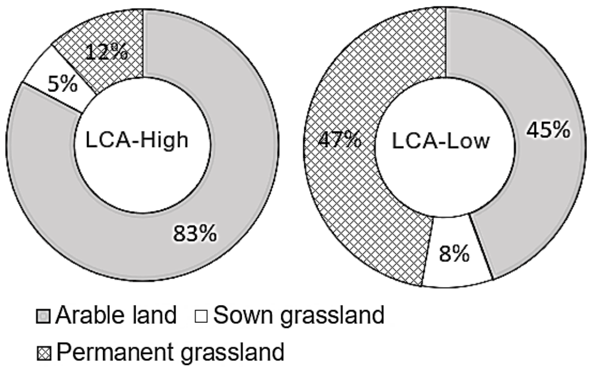

Figure 3. The share of agricultural land management types in 2021 in two studied regions.

The Moran's I test for spatial autocorrelation revealed significant positive spatial autocorrelation for all variables, except for the abandoned area of unproductive SNG in the LCA-Low region in 2014. This suggests that neighboring cells tend to exhibit similar land management patterns. Consequently, we incorporated spatial autocovariates into all of our Generalized Additive Models (GAMs). The relationships between our response variable, which is the abandoned area of SNG, and the explanatory variables varied across the two observation years, between the regions LCA-High and LCA-Low, and between the two SNG types (productive and unproductive), respectively.

Agricultural land management related to abandonment of productive SNG

The Generalized Additive Models (GAMs) applied to both LCA regions and both study periods revealed significant non-linear relationships between the abandonment of productive SNG, the total area of SNG, and the area of permanent grasslands (PG) supported by the agri-environmental scheme for grassland biodiversity (AES) (Fig. 4., Table 3).

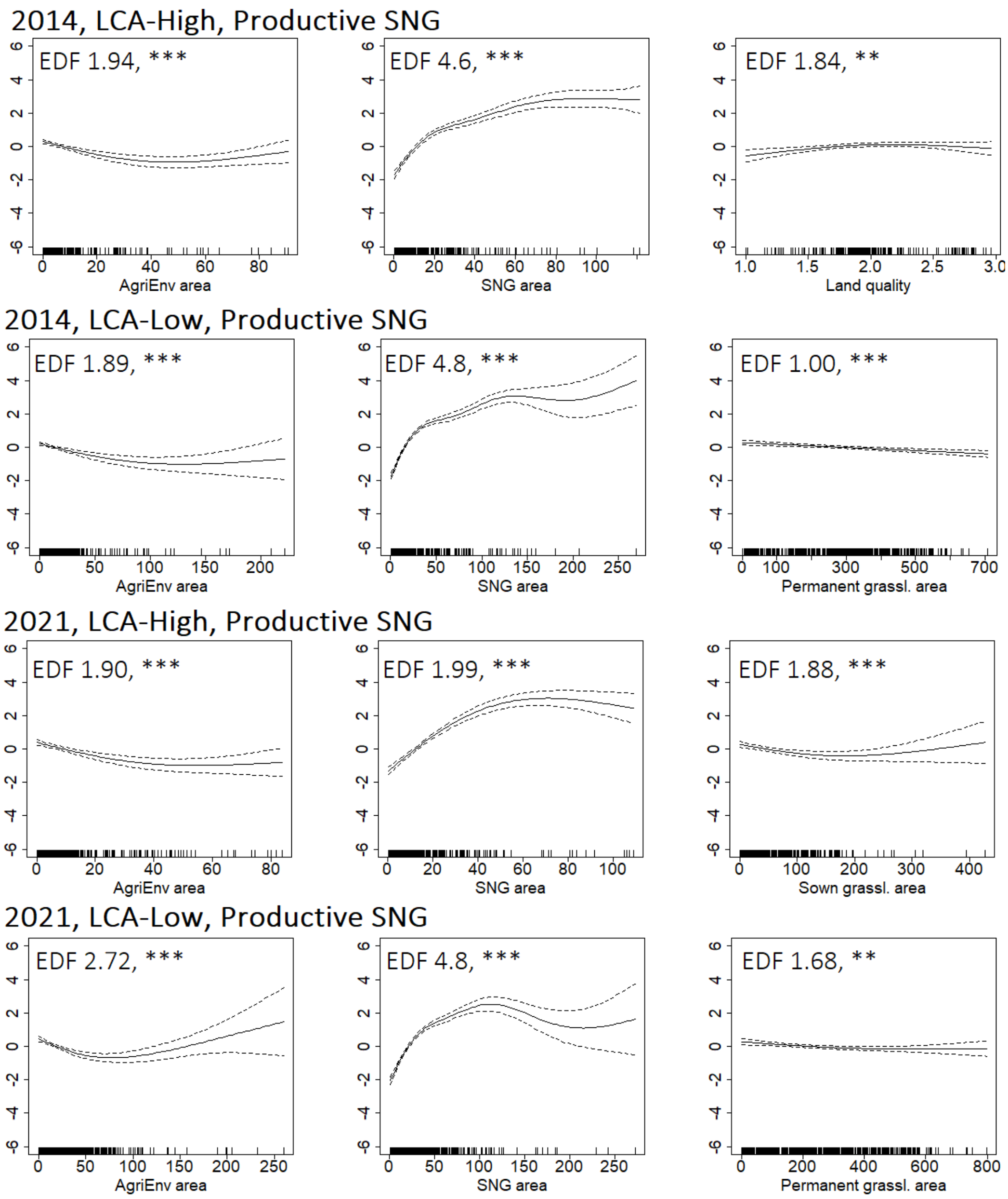

Figure 4. Predictors on *x*–axis against estimated values of response variable (splines) on y–axis for productive SNG. Higher values on the y–axis indicate larger abandoned area. Estimates are represented by a solid line. Dashed lines are 95% confidence limits. Only significant relationships are shown for each model. Significance levels for approximate significance of smooth terms: *** – $p < 0.001$, ** – $p < 0.01$, * – $p < 0.05$, (*) – $p < 0.1$.

Grid cells with a smaller total area of PG managed by AES per grid cell tended to experience higher abandonment rates. However, when grid cells had exceptionally large areas of PG managed by AES (100 ha or more), abandonment rates increased. The significance of land quality, represented by LCA, was associated with abandonment only in the LCA-High region in 2014. It was not significant in the LCA-Low region. In the LCA-High region, a larger area of sown grassland (temporary grasslands) was associated with higher SNG abandonment rates in 2021. In the LCA-Low region, the area of managed permanent grasslands was significantly associated with lower abandonment rates in both study periods.

Table 3. GAM model results for productive SGN

	2014, LCA-High				2021, LCA-High			
	Esti-mate	Std. Error	*t value*	*p*	Esti-mate	Std. Error	*t value*	*p*
(Intercept)	1.28	0.05	26.92	***	0.66	0.06	11.55	***
	edf	*Ref.df*	*F*	*p*	*edf*	*Ref.df*	*F*	*p*
s(PG managed by AES)	1.95	2.00	18.82	***	1.90	1.99	16.22	***
s(Permanent grassl. area)	1.89	1.98	4.19	*	*ns*			
s(Sown grassl. area)	*ns*				1.88	1.99	8.30	***
s(SNG area)	4.60	4.92	97.53	***	1.99	2.00	127.65	***
s(Land quality)	1.85	1.97	5.60	**	*ns*			
s(autocovariate)	*ns*				1.00	1.00	12.41	***
R-sq.(adj)	0.67				0.50			
Deviance explained	67.40%				48.80%			
REML	592.47				604.63			
Scale estimate	0.83				1.32			
Number of observations	257				355			
	2014, LCA-Low				2021, LCA-Low			
	Esti-mate	Std. Error	*t value*	*p*	Esti-mate	Std. Error	*t value*	*p*
(Intercept)	1.26	0.03	36.03	***	1.07	0.04	28.85	***
	edf	*Ref.df*	*F*	*p*	*edf*	*Ref.df*	*F*	*p*
s(PG managed by AES)	1.89	1.99	16.43	***	2.73	2.94	15.80	***
s(Permanent grassl. area)	1.00	1.00	18.12	***	1.68	1.89	6.56	**
s(SNG area)	4.89	4.99	145.2	***	4.83	4.98	91.86	***
R-sq.(adj)	0.73				0.55			
Deviance explained	71.40%				53.40%			
REML	960.15				1209.8			
Scale estimate	0.76				1.01			
Number of observations	434				569			

*** – $p < 0.001$, ** – $p < 0.01$, * – $p < 0.05$, (*) – $p < 0.1$, *ns* – not significant.

These findings underscore the complex interplay of factors influencing the abandonment of productive SNG, with variations between regions and study periods. The total area of PG managed by AES, land capability for agriculture, the area of sown grasslands, and the presence of managed permanent grasslands all contribute to shaping abandonment patterns.

Agricultural land management related to abandonment of unproductive SNG

Abandonment of unproductive SNG was significantly related to the total area of SNG and area of PG managed by AES (Fig. 5., Table 4). Area of sown grasslands was a significant factor in GAM for the region LCA-High in 2014, while in 2021 it was replaced by the area of organic farming. In addition, abandonment of unproductive SNG in region LCA-Low was significantly associated with the arable land area in 2014 and with managed permanent grassland area in 2021.

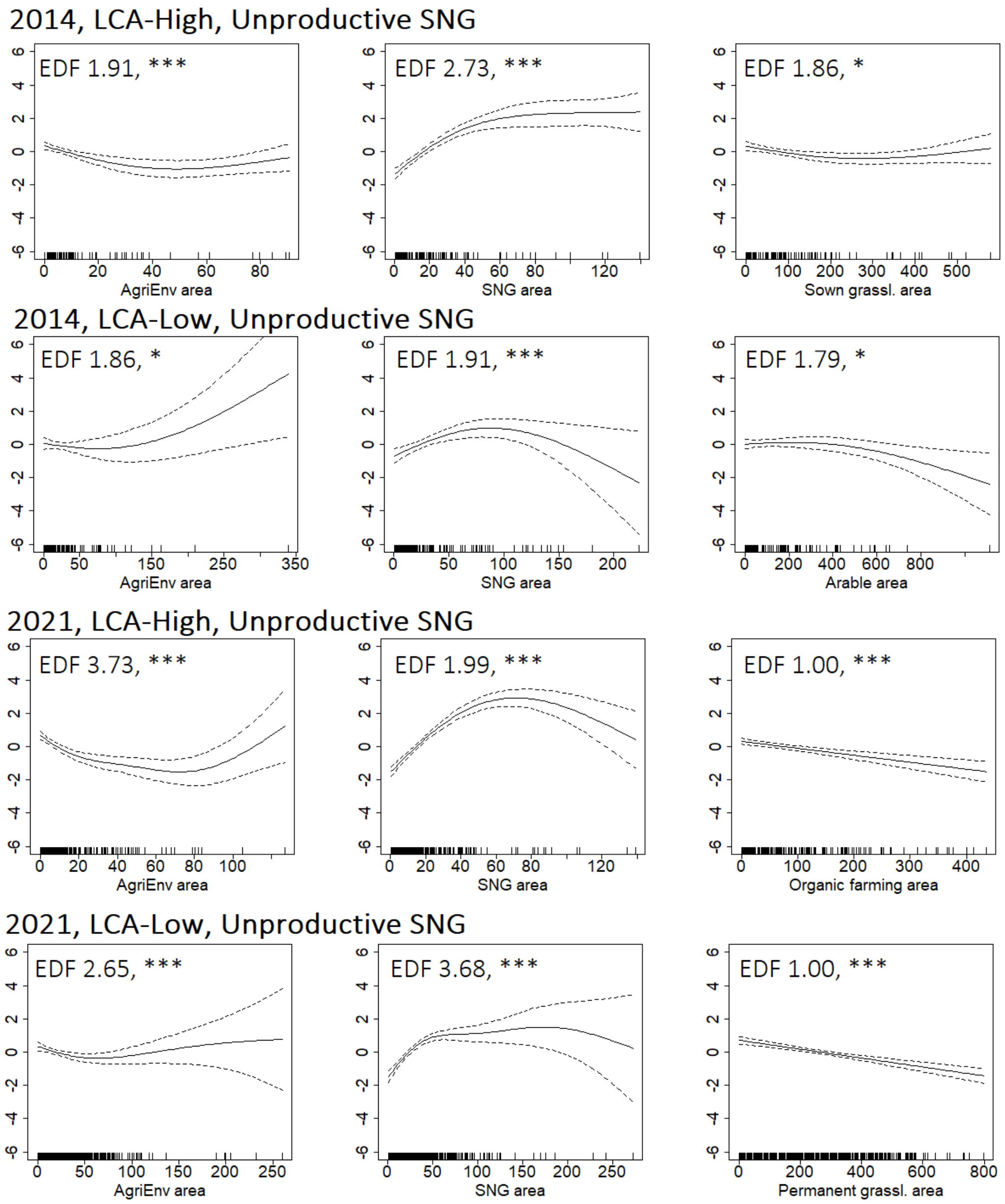

Figure 5. Predictors on x–axis against estimated values of response variable (splines) on y–axis for unproductive SNG. Higher values on the y–axis indicate larger abandoned area. Estimates are represented by a solid line. Dashed lines are 95% confidence limits. Only significant relationships are shown for each model. Significance levels for approximate significance of smooth terms: *** – $p < 0.001$, ** – $p < 0.01$, * – $p < 0.05$, (*) – $p < 0.1$.

Table 4. GAM model results for unproductive SGN

	2014, LCA-High				2021, LCA-High			
	Esti-mate	Std. Error	*t value*	*p*	Esti-mate	Std. Error	*t value*	*p*
(Intercept)	1.13	0.08	14.35	***	0.71	0.07	9.81	***
	edf	*Ref.df*	*F*	*p*	*edf*	*Ref.df*	*F*	*p*
s(PG managed by AES)	1.91	1.99	9.51	***	3.73	4.35	11.30	***
s(Sown grassl. area)	1.86	1.98	5.14	*	*ns*			
s(Organic farming area)	*ns*				1.00	1.00	26.32	***
s(SNG area)	2.73	2.94	33.82	***	1.99	2.00	85.81	***
s(autocovariate)	1.46	1.71	4.23	*	1.51	1.76	8.21	**
R-sq.(adj)	0.58				0.68			
REML	242.35				433.99			
Deviance explained	71.30%				48.50%			
Scale estimate	0.73				1.43			
Number of observations	110				242			
	2014, LCA-Low				2021, LCA-Low			
	Esti-mate	Std. Error	*t value*	*p*	Esti-mate	Std. Error	*t value*	*p*
(Intercept)	0.91	0.10	9.11	***	0.58	0.05	10.65	***
	edf	*Ref.df*	*F*	*p*	*edf*	*Ref.df*	*F*	*p*
s(Arable area)	1.79	1.96	2.87	*	*ns*			
s(PG managed by AES)	1.86	1.97	2.82	*	2.65	3.18	3.15	*
s(PG area)	*ns*				1.00	1.00	46.68	***
s(SNG area)	1.91	1.99	7.92	***	3.68	3.92	24.42	***
s(autocovariate)	*ns*				1.28	1.48	25.18	***
R-sq.(adj)	0.19				0.23			
REML	262.35				717.86			
Deviance explained	18.20%				26.90%			
Scale estimate	1.35				1.49			
Number of observations	134				448			

*** – $p < 0.001$, ** – $p < 0.01$, * – $p < 0.05$, (*) – $p < 0.1$, *ns* – not significant.

DISCUSSION

Our findings partly support our hypothesis that the increased focus on grassland conservation in the CAP from 2007–2013 to 2014–2020 would result in a reduction of SNG abandonment. Overall rate of abandonment decreased during the second CAP period. However, SNG abandonment varied between two CAP periods, showing both positive and negative changes depending on SNG productivity and LCA region.

Relationships between SNG abandonment and agricultural land management

In boreonemoral Europe, semi-natural grassland abandonment ranks as the second most influential factor contributing to the loss of these ecosystems (Penēze et al. 2009; Aune et al., 2018; Rūsiņa et al., 2021). Our study reveals the presence of non-linear relationships between abandonment rates and agricultural land management pattern. Among the seven variables investigated, only two consistently demonstrated significance across all models. Regardless of SNG productivity, CAP period, or LCA region, the lowest proportion of abandoned SNG was most strongly and consistently associated with the higher total area of SNG and the higher area of permanent grassland supported by agri-environment schemes (AES). This finding underscores the influence of historical land use and grassland distribution legacies, aligning with similar observations in other European Union countries. There is a positive link between the success of long-term maintenance of SNG and their total area at the landscape and property levels both in Western European (Guerci et al., 2013; Walden & Lindborg, 2018) and in post-socialist countries. For instance, in Hungary, factors such as grassland patch area and proximity to other grasslands emerged as significant contributors to grassland loss due to abandonment (Biró et al., 2013). Overall, in mosaic-type landscapes agricultural land abandonment is less probable in areas with larger total area of agricultural land (Levers et al., 2016).

In landscapes where the overall area of PG managed under AES was relatively small (less than 100 ha), an increase in latter was effective in slowing down the rate of SNG abandonment. This suggests that CAP subsidies play a crucial role in mitigating the abandonment of SNG in landscapes characterized by small and fragmented grassland areas. However, when the total area of PG supported by AES surpassed this threshold, the rate of SNG abandonment began to increase once more. This phenomenon may be attributed to the fact that eligible areas for AES included not only SNG but also permanent grasslands important for bird species. Research indicates that grassland birds do not necessarily favor botanically rich semi-natural grasslands (Żmihorski et al., 2016). Notably, there was a significantly higher rate of abandonment in the unproductive SNG group when compared to productive SNG in response to an increase in the total area of PG managed under AES. This discrepancy may be attributed to the same underlying factor, albeit with a more pronounced effect. In general, unproductive SNG types hold less importance for grassland birds, often comprising small, fragmented areas that do not provide sufficient open space to meet the needs of these avian species. For instance, many wader species are closely associated with floodplains (Auniņš et al., 2001; Żmihorski et al., 2018; Opermanis et al., 2008), primarily falling within the category of productive SNG (unless subjected to agricultural improvements) under the EU habitat type 6450 *Northern boreal alluvial meadows*. Another crucial grassland bird species, the corncrake *Crex crex*, predominantly relies on post-agricultural permanent grasslands and fallow-lands that do not align with any specific SNG types or EU-designated habitat types (Bellebaum & Koffijberg, 2018; Keišs, 2005; Koffijberg et al., 2016).

These observations suggest that the driving factors behind abandonment differ between these two grassland groups. This divergence is further evidenced by the second most important variable in GAMs - the total area of SNG in the landscape. Notably, the trajectories and steepness of response curves exhibited significant variation between the two SNG productivity groups. The GAMs response curve for productive SNG consistently indicated an increase in SNG abandonment with the enlargement of the total SNG area in the landscape, up to a certain threshold (approximately 50 ha per grid cell), beyond which it plateaued, suggesting a slight positive impact of the total SNG area on their management. Conversely, the GAMs for unproductive SNG displayed a much stronger positive effect of larger SNG areas on the management outcomes of unproductive SNG, resulting in a reversal of the abandonment trajectory.

These findings imply that productive and unproductive SNG tend to be spatially distinct in a landscape, each exhibiting distinct management prospects. Our results align with studies in Central and Western Europe, suggesting considerable differences in threats and pressures among SNG habitat types. For instance, more productive mesic and some wet grassland types in Central Europe are more threatened by intensification (e.g., fertilization and sward improvement through reseeding or plowing), while the majority of unproductive wet and dry grasslands are susceptible to abandonment (Ridding et al., 2015; Janssen et al., 2016; Dengler & Tischew, 2018). Our results confirm this for the boreonemoral region.

In addressing SNG that are threatened by opposing processes (abandonment or conversion to cropland), a one-size-fits-all approach in AES design may not be effective. Instead, result-oriented AES schemes targeting specific problems should be favored over simplistic action-oriented AES (Sabatier et al., 2012). However, AES programs alone may not suffice to reverse the abandonment of SNG. A more integrated approach to nature conservation within the CAP and holistic development strategies are essential to prevent further abandonment (Šumrada et al., 2021).

The differences between two CAP periods

The differences in the response of SNG abandonment to landscape-scale agricultural land management pattern between the two CAP periods indicate both positive and negative changes, depending on the SNG productivity group and LCA region.

The response of productive SNG abandonment remained relatively stable between two CAP periods in both LCA regions. The main distinction was in the response curve to the SNG area in the second period. There, abandonment slowed down with an increased total SNG area, particularly in the LCA-Low region. A similar positive trend was observed for unproductive SNG. This suggests that the CAP 2014–2020 period was favorable for resuming the management of previously abandoned SNG, at least in certain areas. Most probably, unproductive SNG benefited from a substantial increase in the amount of aid from EUR 123 to EUR 206 in the second period, and farmers were more interested in resuming management of these economically non-viable grasslands. In addition, small-scale farmers have limited access to land for agricultural production, and SNG represent their only available option for expanding their production. In Latvia, livestock farming has predominantly been concentrated in regions with low and intermediate LCA, whereas crop farming prevails in regions with high LCA (Nikodemus et al., 2018). The number of cattle and sheep has been consistently increasing in Latvia in the last 20 years (Nipers et al., 2017). These findings align with some other studies examining grassland dynamics during the CAP 2014–2020 period. CAP changes introduced in 2014 led to reduced grassland conversion in Germany (Haensel et al., 2023) and Poland (Wrzaszcz, 2017). Gocht et al. (2017) also projected an increase in the cover of permanent grassland at the European level due to CAP 'greening' measures. On the other hand, SNG could not benefit from dairy farming because it favours intensive land management, minimizing grassland and maximizing the production of crop and maize for fooder (Stypinski, 2011). However, we couldn't find any studies specifically addressing the impact of CAP 2014–2020 on SNG abandonment rates.

The potential negative impact of CAP 2014–2020 on management of productive SNG (increased abandonment) in the LCA-High region could be linked to an increase in the area of sown (temporary) grasslands. Total area of the latter was a significant variable in the GAM for the LCA-High region for productive SNG in 2021 but not in 2014. This suggests that grassland management became more intensive in the LCA-High region during CAP 2014–2020, and it was significantly related to a higher abandonment rate of productive SNG in landscapes with large areas of sown grasslands. On contrary, the area of organic farming was significantly related to a lower abandonment rate of unproductive SNG in the LCA-High region. It is documented that the area of organic farming increased substantially from 2013 to 2020 (Ušča et al., 2023).

Overall, the pattern of unproductive SNG abandonment exhibited less stability across CAP periods. In addition, GAMs for unproductive SNG in the LCA-Low region for both years explained only half as much variation as the other models. This implies that the driving factors behind unproductive SNG management and abandonment are more complex and likely related to socioeconomic factors not considered in this study. One possible explanation is the extreme marginality of these habitats for agriculture for nearly a century. They are most susceptible to abandonment when the profitability of these systems decreases. For instance, low profitability was a key factor driving the recurrent abandonment of recently restored SNG in Sweden. During the 20th century, forest cover in Latvia increased from 23% to more than 50%, primarily at the expense of SNG (Penēze et al., 2009; Rusina & Kiehl, 2010; Rūsiņa et al., 2021). Consequently, the abundance of these habitats was very low in all regions, averaging less than 3 hectares per 25 km^2 grid cell. This aligns with the socioecological habitat extinction vortex concept proposed by Herzon et al. (2022), where a considerable decline in the area under appropriate management eventually leads to diminishing importance for production and reduced attention from policy, research, and development efforts.

CONCLUSIONS

The study reveals significant differences between the abandonment rates of productive and unproductive semi-natural grasslands and intensity of agriculture suggesting that both grassland groups are spatially distinct and face different management challenges and threats.

The response of SNG abandonment to agricultural land management under two CAP periods varied depending on the productivity of the SNG and the land capability for agriculture. These variations suggest that the changes in CAP in relation to grassland conservation have had mixed impacts on SNG abandonment, reducing conversion in some cases but potentially increasing abandonment rates in others.

We conclude that context-specific, regionalized CAP instruments are needed to mitigate grassland abandonment outcomes. As with many similar studies, our study does not imply cause-and-effect relationships between abandonment of SNG and agricultural land management patterns; instead, it suggests that landscape-scale patterns of agricultural land management and land capability for agriculture are still important in shaping grassland biodiversity. It is now vital to investigate the direct effects of implementing CAP instruments on biodiversity at the landscape scale so that the cost-effectiveness of schemes can be evaluated.

Considering our findings, we suggest that result-based agri-environment schemes should be prioritized in landscapes with a high share of extensive agricultural land management. There is an urgent need for detailed research on socioecological drivers of the maintenance and conservation management of SNG, as our study showed their extreme vulnerability to extinction because of their rarity and the lack of positive agricultural land use driving forces in helping to maintain them under appropriate management.

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