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RESEARCH ARTICLE

EU-wide mapping of 'Protected Designations of Origin' food products (PDOs) reveals correlations with social-ecological landscape values

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Abstract

The Geographical Indications (GIs) scheme is the EU's primary policy tool for increasing the market values of geographically distinct food products. Although GIs are linked to the landscapes of food production, little is known about the social-ecological values they represent, mainly due to a lack of spatial data. In this study, we, therefore, mapped all 638 food products labeled as Protected Designations of Origin (PDOs), using NUTS-3 areas as proxies for their actual extent, and correlated their distribution with 13 social-ecological indicators. By compiling this novel dataset, we show that the presence of PDOs strongly overlaps with environmental and cultural values. We reveal positive correlations of PDO frequency with high nature value farmland, semi-natural agriculture, tourism, and cultural heritage indicators. Further, we find that PDOs occur more often in economically weaker areas with older and declining populations. Besides differences in PDO distribution between northern and southern EU countries, we find different correlation patterns across the four largest food categories. For example, cheese and meat products are less correlated to environmental values compared to oils and fats, or fruit, vegetables and cereals. On that basis, we identify the potential of PDOs to support structurally deprived areas and propose PDOs as entry points for sustainable transformation and rural development policies—while simultaneously contributing to the conservation of cultural landscapes and their associated environmental values. As outlined in the Green Deal of the European Union and its Farm to Fork strategy, PDOs should be a part of this transformation. Based on the results of this study, we discuss more specifically for which production systems and under what enabling conditions PDOs are fit for this challenge. We recommend that future governance interventions for a sustainable transformation of EU's agriculture should take the differences across regions and product categories into account.

Keywords Geographical indication · GI · Food labeling · Traditional food landscapes · Cultural ecosystem services · Farm to Fork strategy · High nature value farmland

1 Introduction

Although particular agricultural systems in the European Union (e.g., high nature value farming, or agroforestry systems, as illustrated in Fig. 1 and Fig. 2) can simultaneously accomplish socio-economic and environmental targets, that is still not the case for most of Europe's agriculture (Bouwma et al. 2019; Strohbach et al. 2015). Often, economic targets and market policies are not well-balanced with the goals of environmental sustainability and human well-being (Pe'er et al. 2020). Farming trends in Europe are characterized by intensification and land abandonment processes, resulting in a loss of social-ecological landscape values (Levers et al. 2018; Quintas-Soriano et al. 2022; van Vliet et al. 2015). The European Commission has announced a Green Deal (European Commission 2019a) and a Farm to Fork strategy (European Commission 2021b) for making food systems more sustainable while linking the health of people and nature

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Fig. 1 Open oak landscapes for grazing constitute a large share of the Iberian agroforestry system, also called *dehesa* in Spain and *montados* in Portugal. (photography by the authors).

(Schebesta and Candel 2020). To incentivize this envisioned transformation of food systems, the EU strives to reform the Common Agricultural Policy, however with limited outcomes so far (Navarro and López-Bao 2019; Pe'er et al. 2019). At the same time, private market initiatives labeling food quality and origin are increasingly developed to indicate sustainability considerations and landscape values along the value chain to final consumers (Lusk and Briggeman 2009; van Ittersum

Fig. 2 Open grazing systems in Extremadura based on oak landscapes are home to the famous 'Jamon Iberico' pig meat products. (photography by the authors).

et al. 2007). The Geographical Indications (GIs) scheme was initiated in 1992 to support the incomes of rural communities by certifying the geographic origins of food products (European Council 1992). To date, there is little understanding of the interactions between labeled foods and their landscapes of origin and to what extent Geographical Indications support sustainable landscape management (Ghazoul 2013).

Besides protecting product names as intellectual properties, the scheme also guarantees particular product traits, and traditional processing (Kizos et al. 2017). In 2017, the total volume of sales of GI products reached 7% of the European foods and drinks sector, extra-EU sales reached 15% of the EU's foods and drinks exports, and GI products achieved twice the price of comparable products (European Commission 2020). In previous research, labeling experts have praised the GI scheme as the best option for representing the sustainability of landscape-based products (Flinzberger et al. 2020), and building on that, this paper sets out to investigate this potential in depth.

Food traditions, quality, taste, and regionality are well-defined key characteristics of any Protected Designation of Origin (PDO), which is the strongest of the existing GI labels (Fournier and Michel 2017). To comply with the requirements of the GI regulation, the entire PDO production, processing, and packaging have to take place within a geographically designated area, and a producer group must specify the geographical connection of the product (Higgins 2018). The corresponding EU regulation No. 1151/2012 states "*[…] 'designation of origin' is a name which identifies a product: (a) originating in a specific place, region or, in exceptional cases, a country; (b) whose quality or characteristics are essentially or exclusively due to a particular geographical environment with its inherent natural and human factors; and (c) the production steps of which all take place in the defined geographical area*" (European Council 2012). For the second strictest GI label—the Protected Geographical Indication (PGI)—the same regulation defines that the product characteristics only have to be "*essentially attributable to its geographical origin*" (not exclusively as for PDOs), and that only "*one of the production steps*" needs to take place within the defined area (European Council 2012). This study focuses exclusively on PDO products because PGIs do not always represent the necessary degree of geographic connectedness (Lamarque and Lambin 2015), compared to the PDOs' determining "*inherent natural and human factors*" (European Council 2012). Previous studies have shown how labeling can support the management of cultural and traditional landscapes and sustainable food systems (Escribano et al. 2020; Vandecandelaere et al. 2018), but also that including landscape aspects into product labels is not always easy to achieve (Dias et al. 2015; Mann and Plieninger 2017). PDOs are further supporting rural development (Bérard and Marchenay 2006), and give an economic value to cultural aspects of agricultural landscapes (Belletti and Marescotti 2011). At the same time, the intensification of successful GIs bears the risk of compromising environmental benefits (Belletti et al. 2015; Vakoufaris et al. 2014). Thus, it needs differentiated and specified management practices when employing PDOs as instruments for supporting sustainable food systems.

To date, there is no EU-wide overview of the geographical distribution and extent of PDOs. This is hampering the possibilities of spatial analyses to better understand GIs and their product-landscape relationships. Some countries have started national geo-data platforms providing the spatial data of registered PDO areas, but the data is neither available for all EU countries nor is it accessible in a uniform format. Our study aims at closing this gap by presenting the first map of the regional distribution of all 638 PDO-labeled food products within the EU28 and showing how this distribution pattern correlates with various social-ecological indicators (in this article, we are referring to 'EU27+UK' as 'EU28'). Thereby, we demonstrate the analytical potential of this type of dataset by revealing linkages between high-quality food products and the maintenance of valuable agricultural landscapes. We thus explore why PDOs are an interesting policy option for supporting the sustainable management of culturally imprinted food landscapes.

2 Materials and methods

2.1 Data acquisition

By the end of 2020, 1823 products were registered as Protected Designations of Origin (PDOs) on the European Commission's eAmbrosia database (European Commission 2021a). Although the registration of a PDO requires a group or consortium to define a bounded area in which the product can be produced, the relevant geographical areas have so far been described by plain-text files only. The spatial data partially provided by some national agencies have no uniform structure and are for many countries not available at all. Thus, to carry out a spatial analysis using the distribution of PDOs, we mapped those geographical areas by retrieving the spatial extent from the official text documents describing all product characteristics, including the geographical area. Further, we excluded 1175 wine products. This was done for two reasons: First, we had to reduce the number of products to a reasonable amount to carry out the mapping, handle the data, and also avoid oversampling wine products. Secondly, to align our research with the EU's Farm to Fork strategy, we focused exclusively on food products—reflecting that this strategy also does not mention wines or other alcoholic drinks. Therefore, we carried out the mapping for 638 PDO-labeled food products that had been registered by 30 June 2020 within the EU28.

2.2 Geographical mapping of PDOs

For the mapping of the registered PDOs, we used the European NUTS-3 regions as spatial reference units (the lowest level of the EU's standardized 'Nomenclature of Territorial Units for Statistics'). This territorial unit appeared most useful as many geographical areas of the registered products were defined at local scales close to or equal to NUTS-3. In cases where the spatial extent of PDOs was defined on a finer scale (or limited to certain altitudes), we still mapped the entire applicable NUTS-3 region as a corresponding production area. Also, the statistics from the European Statistical Office (EUROSTAT) or the European Environmental Agency (EEA) were commonly available at the local scale (NUTS-3) or the regional scale (NUTS-2). For these reasons, mapping the PDOs at the NUTS-3 level was a compromise for practicality and data availability. Considering the scale of the EUROSTAT and EEA statistics, all of the correlations between PDOs and social-ecological indicators were calculated at the NUTS-3 level. Some of the older legal documents from the beginning of the GI scheme (1996-1997) were only available as scanned typewritten documents, or in their original language (e.g., only in Greek). In rare cases, legal documents were completely missing and we had to define the geographical area using information from third-party websites. Three bi-nationally registered products (from Slovenia/Croatia and Poland/Lithuania) were treated as separate products in each of the two countries. Three products from non-EU territories of the UK (Jersey and the Isle of Man) were excluded from the analysis, as there were no official statistics available on EUROSTAT for those islands. After mapping each PDO product separately, we merged all the shapefiles for each country and the EU28 countries combined. Subsequently, by dissolving the total dataset by its 1348 NUTS-3 regions, we expressed the number of PDO products that can be produced in every single region—in a 'PDO score'.

2.3 Selecting the social-ecological and structural indicators

To investigate the correlation of the PDO scores with the social-ecological landscape values, we selected 13 indicators (Table 1). The basic criteria for selecting the indicators were complete data availability at either local or regional level and reasonable representativeness for the indicator category (e.g., the number of UNESCO World Heritage sites and the number of tourism beds were used to represent the cultural value of a given region). As presented in Table 1, we acquired eight of the 13 indicators directly from the EUROSTAT database, and two from the EEA database. Institutionally serviced databases like that from EUROSTAT or EEA provided the benefit of uniform data (e.g., regarding the territorial units), and the availability of data as complete as possible. Two more indicators were built from a raster dataset from the 'Copernicus Land Monitoring Service' using Corine landcover data, and the indicator for UN World Heritage sites was constructed from point data acquired from the UNESCO website. All these indicators have previously been used in similar fields

Table 1 Type and origin of social-ecological indicators. The data used for this study were mostly acquired from the official European statistical databases of EUROSTAT and EEA. Below we present the units, data range, sources, and year of each dataset. Indicators marked with asterisks were acquired at NUTS-2 level. [a]Corine (Coordination of Information on the Environment) is an EU landcover classification system. [b]*UAA* stands for utilized agriculture area. [c]*GDP* stands for gross domestic product.

Indicator	Range	Unit	Source	Year
Ecological and cultural indicators				
High nature value farmland	0–81.0	*% of total area*	EEA: eea.europa.eu/.../high-nature-value-farmland	2012
Natura 2000	0–75.0	*% of total area*	EEA: eea.europa.eu/data-and-maps/data/natura-11	2019
Corine[a] landcover richness	0–41.0	*no. of classes*	COPERNICUS: land.copernicus.eu/.../corine	2018
Semi-natural farmland	0–53.9	*% of total area*	COPERNICUS: land.copernicus.eu/.../corine	2018
Tourism beds	0–367,400	*no. of beds*	EUROSTAT: eurostat.ec.europa.eu/...tour_cap	2011
UNESCO World Heritage sites	0–9	*no. of sites*	UNESCO/WHC: whc.unesco.org/en/syndication	2013
Organic farming*	0–54.3	*% of UAA*[b]	EUROSTAT: .eurostat.ec.europa.eu/...organic	2013
Socio-economic indicators				
Population density	2–21,000	*pop. per km*^{2}	EUROSTAT: eurostat.ec.europa.eu/...demo_r_d	2018
Median age	18.1–55.5	*years*	EUROSTAT: eurostat.ec.europa.eu/...demo_r_pjan	2019
5-year population change	−14.5 to 17.0	*% of population*	EUROSTAT: eurostat.ec.europa.eu/...demo_r_pjangrp	2018
GDP[c] per capita	3100–501,600	*Euros*	EUROSTAT: eurostat.ec.europa.eu/...nama_10r_3gdp	2016
Unemployment rate*	0–30.1	*% of population*	EUROSTAT: eurostat.ec.europa.eu/...fst_r_lfu	2019
Average farm size*	0–274	*ha UAA*	EUROSTAT: eurostat.ec.europa.eu/...aareg	2016

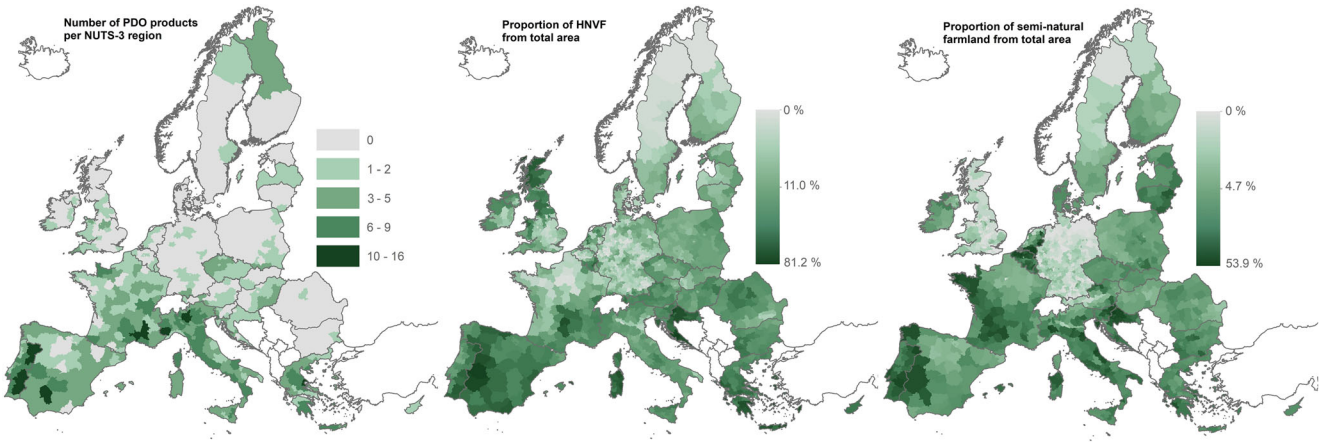

Fig. 3 Distribution patterns among 'Protected Designation of Origin' (PDO) score and two significant indicators. The visually perceivable similarity of the spatial distribution of PDO scores (left), high nature value farmland (HNVF) (center), and semi-natural farmland (right) already indicated a correlation. NUTS-3 is the abbreviation for the lowest scale of the European Unions 'Nomenclature of territorial units for statistics'.

of research as useful proxy values for social-ecological assessments (Bennett et al. 2018; Malek et al. 2018; Raymond et al. 2016). We selected environmental indicators based on their relationship with landscape values. High nature value farmland (HNVF), which features many forms of small-scale, less-intensive, and traditional agricultural lands (Lomba et al. 2019), was selected as a key indicator because of its holistic connection to social-ecological landscape values (Kizos et al. 2012; Plieninger et al. 2019).

The proportion of Natura 2000 areas, a pan-European network of protected areas, was selected because sustainable farming in these protected areas has environmental benefits (Underwood 2014). For HNVF and Natura 2000, a visual similarity of distribution patterns with the PDO score is apparent and, for illustrative reasons, is presented in Fig. 3. The richness of landcover and the percentage of semi-natural agricultural farmland (including agroforestry) were included as additional indicators of environmental value. Landcover richness was calculated from the number of Corine landcover classes present in a given region, and semi-natural agriculture was calculated as the percentage of the land covered by one of three Corine landcover classes: agroforestry, agricultural land with nature areas, and complex agricultural patterns. Further, the number of tourism beds and UNESCO World Heritage sites represented multi-dimensional aspects of cultural values (Parga-Dans et al. 2020). Standard agricultural and socio-economic datasets from EUROSTAT were used as indicators of prevailing farm structure and socio-economic development of a given region.

2.4 Descriptive statistical analysis

The number of PDO products attached to each region—the PDO score—formed the value against which we tested correlations for the 13 social-ecological indicators. Our main analysis method was a separate spatial correlation of the PDO score and each of the 13 selected indicators. Thereby, all 1348 NUTS-3 regions were included in all calculations, even those in which no PDOs occurred. All correlations were calculated at the NUTS-3 level (as explained in section 2.2). Indicator data acquired at the NUTS-2 level was downscaled to NUTS-3, assuming the same values for the subordinate regions. In addition to the overall correlations, we calculated the specific regional and product category correlations for all 13 indicators. Regionally, we split the dataset into the Mediterranean countries (IT, FR, ES, GR, PT, HR, SI, CY), and the rest of the EU28 (not considering Malta for the Mediterranean, as it had no registered PDO). Further, we distinguished the four most frequent product categories, namely meat (categories 1.1 and 1.2), cheeses (1.3), oils and fats (1.5), and fruit, vegetables and cereals (1.6). Fresh meat (1.1) and processed meat (1.2) were treated as a combined category throughout the entire study, and the category 'other products of animal origin' was not considered at all, as it included products of disparate characteristics (e.g., eggs, honey, and dairy products). For the total PDO dataset and all the above-mentioned product categories, we calculated the PDO score separately. By using the numerical values of the PDO score, we created heatmaps showing hotspots and clusters of PDO production in the European Union (Fig. 4), and we also differentiated the heatmaps by product categories (Fig. 5).

The correlation values in the smaller sub-samples (e.g., non-Mediterranean countries, which had only 96 of the 638 PDOs) can differ due to unknown causalities, or the correlation can be small or non-significant because of the small sample. However, the overall trends showed no signs of statistical-methodological artifacts that cannot be explained in this way. For example, organic farming

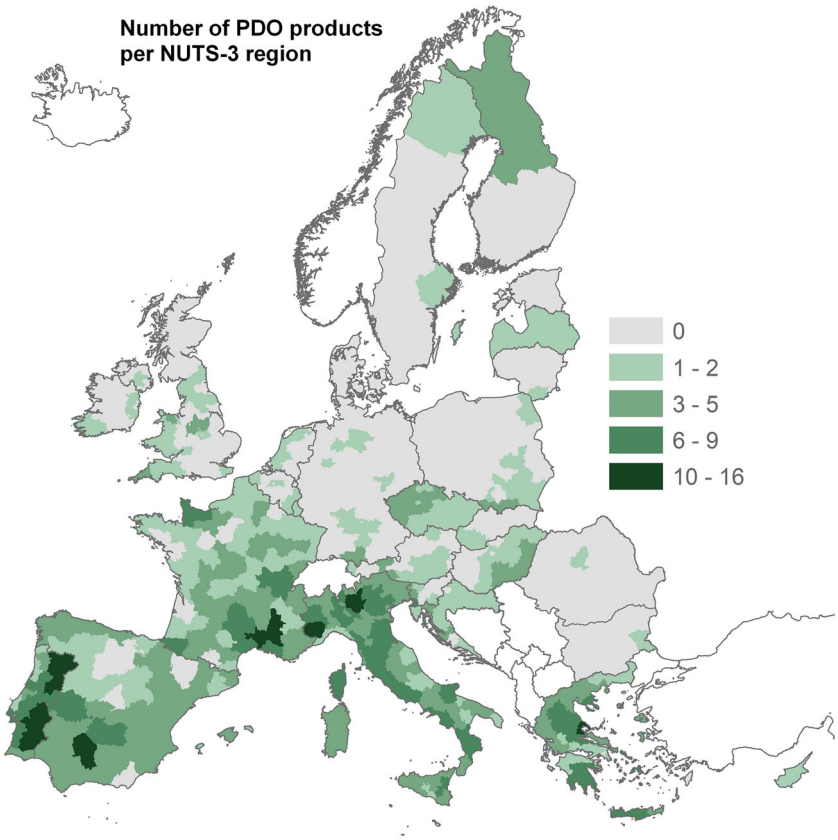

Fig. 4 'Protected Designation of Origin' (PDO) distribution in the former European Union 28 member states. The map presents the number of PDOs that can be produced in each NUTS-3 region (indicated by lighter and darker shades of green), revealing hotspots in Portugal, Spain, France, Italy, and Greece, and showing the Mediterranean dominance. NUTS-3 is the abbreviation for the lowest scale of the European Unions 'Nomenclature of territorial units for statistics'.

did not correlate significantly with any of the product categories. Also, the correlations with most of the agricultural and demographic indicators were small or non-significant for the rest of EU28 but were consistent for the Mediterranean countries. Finally, to relate the correlations of different product categories to the average size of the legally registered area, we calculated the area sizes for all PDOs and averaged them for all sub-categories using arithmetic means. Although the sizes of the PDO areas can be influenced by the different sizes of NUTS-3 areas, generally the NUTS regions are meant to divide the territory into units with similar population numbers.

3 Results

3.1 Spatial distribution of PDOs

PDO-labeled foods were found to be unequally distributed across geographical areas. At a national level, 84.9% of the products (542 out of the 638) were registered in eight Mediterranean countries: Portugal, Spain, France, Italy, Slovenia, Croatia, Greece, and Cyprus. At the local level, we identified five regions with ten or more registered PDO products (hotspots of PDO production) in western Portugal, southern Spain, northern Italy, southeast France, and a small area on Greece's mainland (Fig. 4). On a regional scale, the larger areas of high PDO abundance were found in Portugal, southern Spain, southern France, northern Italy, Sicily, and Crete. The PDOs were dominated by cheeses (30.1%), fruit, vegetables and cereals (23.7%), and oils and fats (18.5%), complemented by fresh (6.6%) and processed (6.0%) meat products. We found no relevant difference between the Mediterranean and non-Mediterranean countries in their relative shares of fruit, vegetables and cereals, cheese, and meat PDOs. By contrast, oils and fats PDOs were ten times more frequent in the Mediterranean countries (21.4% vs 2.1%). The average size of a PDO-producing area was around 13,000 km^2, but the average meat PDO extended across a considerably larger territory (over 23,000 km^2). While the average cheese PDO covered almost 14,000 km^2, the average oils and fats PDO covered around 9300 km^2, and the average fruit, vegetables and cereals PDO around 8500 km^2 (Table 2).

3.2 Correlation of PDOs and social-ecological indicators

All environmental and cultural indicators (except for organic farming) showed a clear positive correlation for most product categories (Table 3). The presence of high nature value

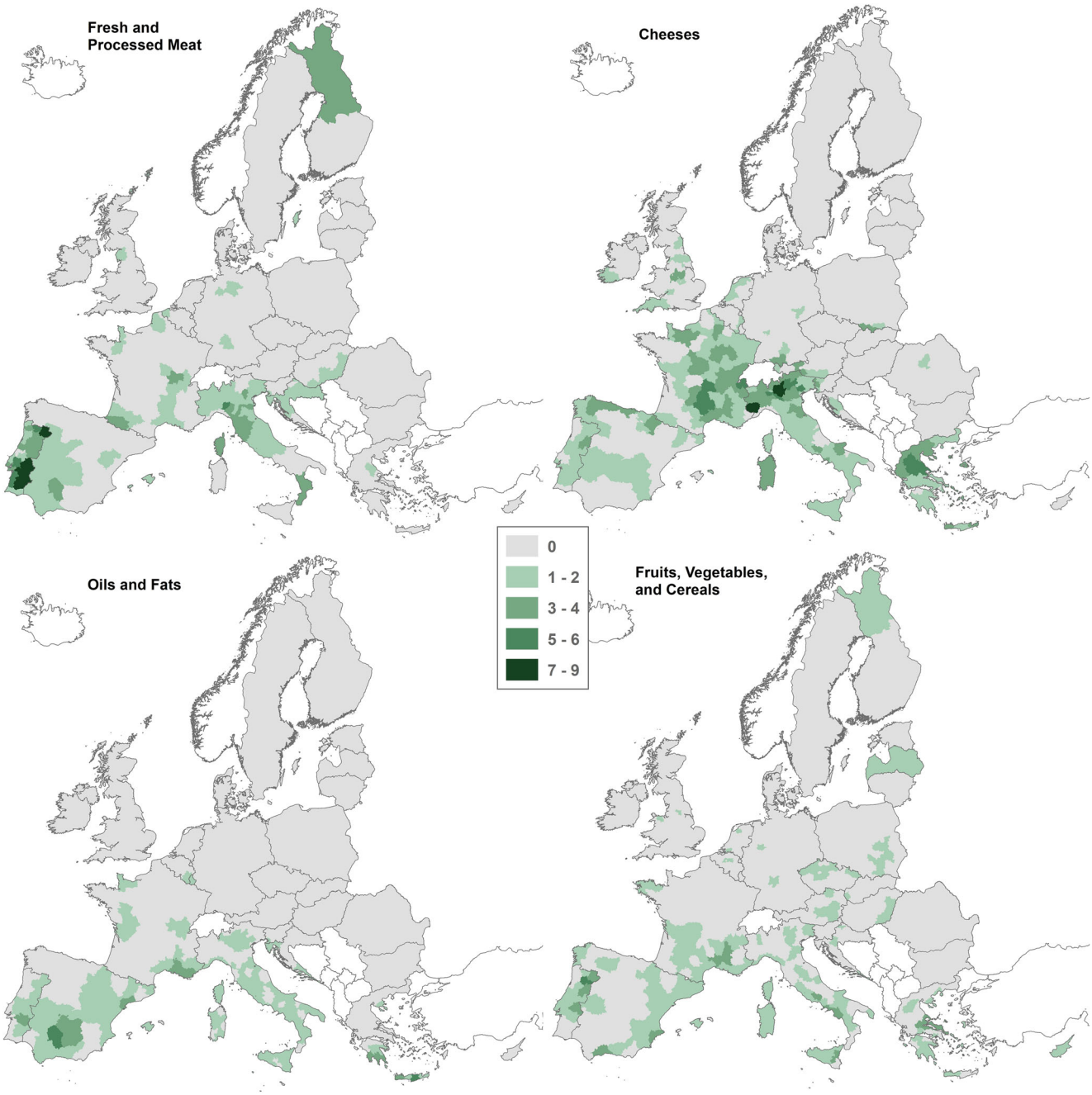

Fig. 5 Spatial distribution of the most frequent product categories. Different types of PDO products are distributed differently across Europe. At NUTS-3 level, meat and cheese products show more pronounced hotspots and higher degrees of clustering than oils and fats, or fruits, vegetables, and cereals. Green shades indicating the number of PDOs present in each NUTS-3 region. NUTS-3 is the abbreviation for the lowest scale of the European Unions 'Nomenclature of territorial units for statistics'.

farmland (HNVF), the share of semi-natural agricultural landcover, and the number of different Corine landcover classes (CLC richness) in a given region had the strongest correlations overall. The correlations of the PDO score (number of PDOs in each NUTS-3 region) with Natura 2000 areas, with the number of UNESCO World Heritage sites, and with the number of tourism beds were lower, but they showed the same pattern. Stronger correlations were found for the sub-samples of oils and fats, as well as fruit, vegetables and cereals (Table 3). HNVF and the number of tourism beds were correlated strongly and positively with the non-Mediterranean PDO scores, but landcover richness and semi-natural farmland were correlated more strongly with PDO scores in Mediterranean countries. Semi-natural farmlands showed the strongest correlation with the frequency of meat PDOs out of all the food categories. Remarkably, organic farming was not

Table 2 Total 'Protected Designation of Origin' (PDO) numbers and average sizes of production areas (in km^2). The five most frequent product categories were selected for this study, as they dominate most of the PDO market. The total numbers of PDOs and the average sizes (arithmetic means) of legally registered production areas are differentiated by product categories and regions. The categories were copied from the EU eAmbrosia database. Fresh meat and processed meat were merged into one category.

	Overall		Mediterranean		Non-Mediterranean	
PDO category	Number of PDOs	Avg. size [km^2]	Number of PDOs	Avg. size [km^2]	Number of PDOs	Avg. size [km^2]
Fresh and processed meat	80	23,809	67	19,889	13	43,710
Cheeses	192	13,827	160	15,382	32	6051
Oils and fats	118	9229	116	9329	2	3441
Fruit, vegetables and cereals	151	8526	130	7646	21	14,014
Other products of animal origin	37	10,379	31	10,995	6	7197
Fresh fish	12	26,437	5	8298	7	39,393
Other products (spices, etc.)	30	18,434	20	12,757	10	29,787
All other categories	18	7013	13	6356	5	8724
Total	638	13,011	542	12,136	96	17,953

correlated with the presence of PDOs. All the demographic indicators showed a spatial overlap between PDO scores and rural regions with smaller, declining, and older populations. For these three indicators, this relationship was stronger for the Mediterranean countries and weaker, or non-significant, for the non-Mediterranean countries, which had a considerably smaller sample size of PDO products. Median age and a 5-year population decline also showed their strongest correlations for meat PDO scores compared to other food categories (Table 3). In economic terms, a lower GDP per capita and a higher unemployment rate were correlated with PDOs. GDP per capita was mostly indifferent among most

Table 3 Correlations of the 'Protected Designation of Origin' (PDO) score and 13 social-ecological indicators. Results of the paired correlations, differentiated by product categories and regions (p-values $p < 0.05$: *). Correlations that are relevant for the discussion are printed in bold. [a]*Med.* stands for Mediterranean. [b]Corine (Coordination of Information on the Environment) is an EU landcover classification system. [c]Semi-natural farmland includes three Corine landcover classes: 'agroforestry', 'agricultural land with nature areas', and 'complex agricultural patterns'. [d]*GDP* stands for gross domestic product.

Indicator	All EU28 products	Meat (fresh or processed)	Cheeses	Oils and fats	Fruits, vegetables, and cereals	Med.[a] countries	Non-Med.[a] countries
Ecological and cultural indicators							
High nature value farmland	**0.39***	0.22*	0.27*	**0.29***	0.27*	0.09	**0.20***
Natura 2000	**0.22***	0.09*	0.13*	**0.20***	0.16*	0.03	0.05
Corine[b] landcover richness	**0.48***	0.28*	0.30*	**0.36***	**0.36***	**0.33***	0.12*
Semi-natural farmland[c]	**0.39***	**0.32***	0.21*	0.24*	0.28*	**0.13***	0.05
Tourism beds	**0.22***	0.09*	0.13*	**0.22***	0.17*	0.09	**0.20***
UNESCO World Heritage sites	**0.23***	0.11*	0.13*	**0.21***	0.18*	0.13*	0.14*
Organic farming	−0.06*	−0.03	−0.05	−0.02	−0.03	−0.05	−0.02
Socio-economic indicators							
Population density	**−0.14***	−0.09*	−0.09*	−0.08*	−0.09*	−0.15*	−0.10*
Median age	**0.17***	**0.18***	0.15*	0.06*	0.09*	**0.30***	−0.05
5-year population change	**−0.23***	**−0.21***	−0.12*	−0.12*	−0.14*	**−0.12***	0.02
GDP[d] per capita	**−0.13***	−0.07*	−0.06*	−0.08*	−0.10*	0.01	−0.05
Unemployment rate	**0.44***	0.16*	0.37*	0.37*	**0.33***	**−0.18***	−0.01
Average farm size	**−0.20***	−0.13*	−0.14*	−0.14*	−0.15*	**−0.18***	0.05

sub-categories, being slightly more negatively correlated for fruit, vegetables and cereals. A strikingly high correlation of unemployment rates with the overall PDO score stood in contrast to a negative correlation for the Mediterranean sub-sample. Among the product categories, the frequency of meat PDOs showed the smallest correlation with unemployment rates. Smaller average farm sizes were correlated with PDO scores but not for non-Mediterranean countries.

4 Discussion

To gain a better understanding of how well 'Protected Designations of Origin' (PDOs) reflect multiple values of agricultural landscapes, we related the spatial extent of PDOs to different social-ecological indicators on a large spatial scale. A major barrier limiting research on 'Geographical Indications' (GIs) was the lack of precise and digitally available geographical data regarding the delimitation of PDO regions—a prerequisite for research, monitoring, and management. For a comprehensive investigation, our self-mapped subset of PDOs covered all 638 food PDOs in the EU28 (by 30 June 2020). We derived from our results that PDOs have a well-established relationship to landscape values. For the correlations, we grouped the registered PDO products into four food product categories (meat, cheese, oils and fats, and fruit, vegetables and cereals), revealing recurring patterns of landscape-product relationships. Further, by differentiating between the Mediterranean and the non-Mediterranean countries, we found a substantial difference in both the number of registered PDOs and the correlations with landscape characteristics. However, the relatively small number of non-Mediterranean PDO products led to less significant correlations (see significance markers in Table 3).

4.1 PDOs are predominantly located in the Mediterranean countries

An obvious difference between southern and northern Europe is the number of registered products, with 85% of PDOs being produced in eight Mediterranean countries. The underlying reasons for this may be found in traditions regarding landscape management and food cultures as represented by the Mediterranean diet. Further, political support for PDO registration as well as the climatic and environmental prerequisites (e.g., higher levels of biodiversity) may have played a role in some Mediterranean countries (Kizos et al. 2017; Quiñones-Ruiz et al. 2016). A consequence of these complex and not fully understood causalities is that PDOs are economically a lot more relevant in the Mediterranean food sector, while in non-Mediterranean countries, they are mostly niche products (Spiller and Tschofen 2017). This becomes particularly evident in the positive correlation between the employment rate and the number of PDOs within the Mediterranean countries. The fact that high nature value farmland (HNVF) showed a stronger relationship with PDO scores in the non-Mediterranean countries could be another result of more niche-market PDOs, which target few extraordinary landscapes and aim mostly for domestic markets. In comparison, the production of highly successful Mediterranean PDOs—cheeses in particular—is oriented towards mass markets and global exports. Those cheese PDOs feature high volumes of annual production: For example, around 200,000 tons of Grana Padano (clal.it 2021), 120,000 tons of Feta (dairyreporter.com 2021), and 70,000 tons of Comte (agri71.fr 2021) are produced every year.

Population decline and aging populations were only correlated with the PDO scores in Mediterranean countries. At the same time, we found stronger correlations between landcover richness and semi-natural farmland in Mediterranean countries. Thus, a promising strategy for further PDO development in the Mediterranean may be to harness social-ecological synergies, by linking the improvement of rural livelihoods with the maintenance of valuable agricultural landscapes. However, for such synergies to happen, PDOs would need to support land management practices that are more clearly directed towards environmental and cultural values, such as agroforestry, low intensity and mosaic-like land use, silvopastoral grazing systems, or HNVF practices (García-Martín et al. 2021). Like HNVF, the number of tourism beds was more strongly correlated with the PDO score in the non-Mediterranean countries, pointing towards a more selective registration of PDOs in environmentally valuable and culturally unique regions. The high number of PDOs in the Mediterranean is possibly also rooted in the high societal importance of the Mediterranean diet—acknowledged as an intangible cultural heritage by UNESCO (Bonaccio et al. 2021). Based on a high degree of biodiversity, more regional and typically traditional products evolved in the Mediterranean (Blondel 2006; Padilla et al. 2012). We assume that because of the Mediterranean diet's societal importance, regionality and product quality of food have been more important to Mediterranean consumers long since (Escribano et al. 2020). The fact that the Mediterranean diet has been proven to be healthier and more sustainable than the average north European diet probably makes PDOs a suitable instrument for promoting sustainable and healthy food systems as well.

4.2 PDOs target environmentally and culturally valuable landscapes

The consistent correlations between the presence of PDOs and our indicators of environmental and cultural values pointed towards a strong representation of low-intensity and traditional farming systems in PDO production. Those characteristics are often linked to the concept of HNVF, especially in the

Mediterranean region (Plieninger et al. 2021). The presence of PDOs showed a particularly strong congruence with HNVF areas, which are described as small-scale, extensive, traditional, and diverse systems (Lomba et al. 2019). Natura 2000 areas also overlapped with PDO production areas, probably because many of these protected areas include low-intensity livestock grazing systems on marginal and less productive lands (Underwood 2014). The richness of landcover and semi-natural farmland (two indicators based on Corine landcover data) also correlated with the presence of PDOs. The fact that a combination of agroforestry, agricultural land with natural areas, and complex agricultural patterns showed a clear positive correlation for all sub-categories may be the consequence of PDOs coinciding with structurally and functionally diverse landscapes. Also, the occurrence of PDO hotspots on the Iberian Peninsula, in Italy, and Greece reflected this revealed relationship, as the Mediterranean Basin is recognized as an HNVF hotspot of Europe (García-Martín et al. 2021; Plieninger and Bieling 2013).

Many PDOs are an inherent part of multi-functional agricultural systems. By contrast, a stronger specialization in single, internationally traded products can reduce the environmental benefits of originally sustainable landscape management (García-Martín et al. 2021). Regarding the large extent of some PDO areas being registered—for example, the Italian '*Salamini Italiani Alla Cacciatora*' covering around 50% of Italy's territory, or '*Český Kmín*' covering the whole of the Czech Republic—we have slight concerns too. There should be some scrutiny if such large PDO territories make sense, given that it is impossible to establish strong linkages to distinct landscapes at such vast geographic scales. For further research, we suggest investigating under which circumstances large farm sizes can lead to less desirable environmental and socio-demographic production characteristics.

Assuming that the numbers of tourism beds and UNESCO World Heritage sites are indicators for cultural appreciation, PDO-rich regions appear to be touristically attractive. The PDO scores for fruit, vegetables and cereals, as well as for oils and fats PDOs, were correlated more strongly with cultural appreciation than cheese or meat PDOs, possibly because the respective animals are not always part of the landscapes but kept in staples. Therefore, we assume that the categories of plant-based PDOs are more closely related to culturally relevant landscape features and thus represent the emotional and aesthetic attachment to their landscapes of origin more clearly. Similarly, silvopastoral grazing systems like the Mediterranean grazed oak woodlands (*Dehesas* and *Montados*) are known for being embedded into highly aesthetic cultural landscapes (Plieninger et al. 2015; Scolozzi et al. 2012) and for being associated with conservation values (Bugalho et al. 2011). This may explain the stronger correlation between semi-natural farmlands and PDOs from the Mediterranean countries (e.g., '*Presunto do Alentejo*' or similar pig meat products, widely known as '*Jamón Iberico*').

The absence of a correlation between organic production and PDOs may reflect competing ideals in the organic vs regional food debate. For instance, Denmark has the highest share of organic sales values by far, but there is not a single PDO registered in the country (European Commission 2019b).

4.3 PDOs are linked to rural areas lagging behind in socio-economic development

By design, PDO food products are targeted at rural regions and are deeply embedded into the traditional socio-economic systems of these regions (Egea and Pérez y Pérez 2016; Raimondi et al. 2018). However, our analysis showed that PDOs are not explicitly linked to successful rural development. On the contrary, PDOs occurred more often in areas for which the indicators pointed towards a rural exodus, characterized either by the abandonment of land management and social structures (van Vliet et al. 2015), or by intensification processes (Bruno et al. 2021). Unlike the results for cultural values, it appeared that the presence of PDOs was negatively correlated with the economic success of a region (as expressed by GDP). Although unemployment rates showed a relatively strong correlation with PDOs in general, it was the opposite for PDOs in the Mediterranean countries (Table 3). At the same time, smaller farm sizes were significantly correlated with a higher number of registered PDOs within the Mediterranean only (not so in non-Mediterranean countries). Field research based on case studies is necessary to fully capture the meanings of these and other correlations and to investigate how PDOs can contribute more comprehensively to rural development. We speculate that the idea of the GI scheme to support rural livelihoods (particularly in marginalized areas) does work, but there is potential for improved performance.

PDOs were even more strongly correlated with older and declining populations than with low population densities. Thus, the demographic situation of PDO-rich regions is not only geographically remote or socio-economically marginalized in a static sense, but characterized by a trend towards rural exodus. In the Mediterranean region—home to most PDOs—the higher average median age of the population was even more strongly correlated with PDO presence. This trend towards rural out-migration, with a lack of labor and a cultural drain, can threaten the maintenance of traditional agricultural landscapes and related sustainable management practices, and finally, lead to the complete disappearance of the traditional systems. The high correlation of meat PDOs with older and declining populations went along with a lower correlation for unemployment. These diverging trends show that, although a population decline may pose a threat to the maintenance of

PDOs in general, it may be successfully tackled with finely tuned approaches that consider the different product categories. As we have shown that PDOs occur more often in demographically deprived rural areas, we see it as a promising future task to investigate which product types could be particularly helpful for improving rural situations and livelihoods.

While PDOs mainly represent traditional products and practices, innovation and climate change adaptation are also important for maintaining their market relevance and attracting consumers. Especially concerning climate change and agriculture, the PDO-rich Mediterranean region will be one of the most affected regions in Europe (Schröter et al. 2005). Already today, certain plant species or varieties that are necessary raw materials for PDO products are threatened by climate-change-induced droughts or pests (Chacón-Vozmediano et al. 2021; Clark and Kerr 2017). However, the literature shows an imbalance in the amendments to PDOs (updates to their legal documents) targeting economic aspects way more often than environmental or cultural aspects (Quiñones-Ruiz et al. 2018).

4.4 Correlations between PDOs and social-ecological values vary between food products

Looking at the four food categories (meat, cheeses, oils and fats, and fruit, vegetables and cereals) separately, we revealed different spatial hotspots for each category (Fig. 5) and found relevant differences regarding the correlations with indicators for social-ecological values (Table 3). For example, 77% of the income from cheese GIs—the category with the highest sales volume by far—is generated in four Mediterranean countries: Italy, France, Greece, and Spain (European Commission 2020). At the same time, the production areas of cheese PDOs were, on average, almost three times larger in Mediterranean than in non-Mediterranean countries (Table 2). While meat products were spatially concentrated in regions of western Portugal (which are dominated by open grazing woodlands), cheese PDOs were most frequent in southern France, and northern Italy (where more industrialized milk production occurs). However, we acknowledge that cheese and meat PDO products, in particular, have been historical core products of the GI scheme (European Commission 2020), and in some cases are the economic basis for landscape maintenance (Bérard and Marchenay 2006). For further research, it will be interesting to see to what extent the landscape concept behind PDOs is congruent with other usages of the landscape concept—especially for conservation purposes.

Oils and fats showed less pronounced hotspots, but they were almost exclusive to the Mediterranean landscapes with their semi-arid climate and longer vegetation periods. Finally, 'fruit, vegetables and cereals' was the most evenly spread category, with only small hotspots in Portugal, central Italy, and northern Greece. Despite similar total numbers of registered PDOs (Fig. 5), we observed less structural clustering for oils and fats, and fruit, vegetables and cereals, probably indicating more dispersed production patterns than for meat or cheese. Also, many legal documents for olive oil PDOs limit the production intensity to a certain threshold, to protect the underlying ecosystems and prevent quality trade-offs (Belletti et al. 2015). Furthermore, the difference in the average geographical area for the different PDO categories was considerable. The average PDO area for processed meat (23,800 km^2) was around two and a half times larger than the average PDO area for oils and fats (9200 km^2) or fruit, vegetables and cereals (8500 km^2). PDO-labeled cheese products also featured larger areas on average (13,800 km^2) and especially large areas in the Mediterranean countries (15,400 km^2) (Table 2). From this, we conclude two-fold: First, that animal-based PDOs need larger territories to source enough animal food supply, and second that PDOs with larger production volumes need larger territories as well. Also, some PDO clusters based on open grazing systems may have evolved in specifically suitable and unique landscapes. The natural characteristics of grazing systems such as the *Dehesas* and *Montados* of Spain and Portugal, or the *Cévennes* in Frances favor low-intensity production and hence comprise larger PDO territories for grazing animals (Berriet-Solliec et al. 2018). Overall, it appeared that PDOs for more highly processed foods, such as meat or cheese, were rooted in economically stronger regions. That makes sense given the higher added value within higher processed food products. At the same time, those further processed products also appear to develop larger clusters with more centralized processing units. Further investigation could test whether the correlations for highly intensified wine production systems—which economically make up a relevant part of the GI scheme—support these assumptions.

5 Conclusions and policy recommendations

The mapping of 638 PDO products at the level of the EU's NUTS-3 regions revealed novel insights into the present system of Geographical Indications (GIs). Based on our correlations of this map with social-ecological indicators, we identified three potentials for the PDO label, specifically concerning the implementation of the EU's sustainability agenda as outlined by the Green Deal and the Farm to Fork strategy.

First, we have shown that particularly the occurrence of oils and fats, as well as fruit, vegetables and cereals labeled as PDOs, is more strongly linked to environmental and cultural values, compared to meat or cheese PDOs. PDO requirements will need to address these significant differences in terms of environmental quality, socio-economic viability, and production structures to indicate more homogenous production characteristics to consumers. Landscape features, as well as environmental integrity and connectivity, are essential elements to

be taken into account when implementing the Farm to Fork strategy within the GI scheme. Given the risks of an economically motivated over-intensification of PDO production on the one hand and large production areas with questionable landscape-product relationships on the other hand, we recommend a general fitness check of the PDOs. As the Farm to Fork strategy itself has been criticized for the generic nature of its goals (Schebesta and Candel 2020), a potential PDO fitness check should assess whether the original idea of local food products is preserved. It has to be ensured that PDOs are tightly linked to their landscapes of origin and that sustainable management will be possible under future circumstances regarding demography, ecology, and climate.

Secondly, our results show that PDOs provide a powerful, but not very effectively used potential to contribute to income opportunities in rural regions. While it seems that the environmental benefits of PDO production vary across different product types, the linkage with negative demographic trends seems to be the normality. Therefore, we recommend making further use of PDOs to support the development of rural areas. To do so successfully we see a great necessity to carry out qualitative case studies at a farm and landscape level, investigating PDO producers' motivations, value chains, and interests of external stakeholders and the public.

Lastly, current debates on sustainable food systems identify meat consumption and animal products as key issues for our environmental footprint. However, our results show that PDO-certified meat production can coexist with environmentally valuable landscape features. Instead of treating meat from all origins identically, we believe that PDO-certified production systems can be role models for a 'less but better meat' mindset. That, in turn, would require implementing conditions for PDO certification (and potentially CAP subsidies) to manage grazing systems sustainably: Providing ecosystem services, maintaining habitat structures as well as cultural landscape features, contributing to public health, and reducing greenhouse gas emissions should become more profitable. Considering the meat- and cheese-dominated past of the PDO label, the role of plant-based PDOs could also be strengthened within the GI scheme. In cases where low degrees of processing lead to little added value, this could be increased by highlighting the use of PDO-labeled raw products as ingredients. Thus, further processed products could receive an additional label indicating the partial use of a PDO.

If used and adapted wisely, we believe that Geographical Indications in general and PDOs, in particular, can be important elements for both conserving traditional heritage and promoting sustainable innovation. Thus, we suggest maintaining and developing PDOs as income sources for structurally weak rural regions while at the same time using their potential for contributing to the United Nations Sustainable Development Goals.

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Authors' contributions All authors had the idea for this article and designed the methodology. LF was responsible for the mapping process, its implementation, data analysis and data management, and writing of the manuscript while receiving constant feedback from YZ, MB, and TP. All authors critically contributed to the draft and approved the final version for publication.

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Data availability The original data on which the results of this study are based (including the PDO score datasets, and the social-ecological indicator datasets), can be accessed through the Zenodo repository under the following link: https://doi.org/10.5281/zenodo.6483031

Declarations

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