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Identification of representative dairy cattle and fodder crop production typologies at regional scale in Europe

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Abstract

European dairy production faces significant economic, environmental, and social sustainability challenges. Given the great diversity of dairy cattle production systems in Europe, region-specific concepts to improve environmental and socioeconomic sustainability are needed. Regionally integrated dairy cattle-crop systems emerge as a more resilient and sustainable alternative to highly specialized farming systems. Identifying different dairy cattle production typologies and their potential interactions with fodder crop production is presented as a step in transitioning to optimized agricultural systems. Currently existing typologies of integrated systems are often insufficient when characterizing structural, socioeconomic, and environmental components of farms. We fill this gap in the literature by identifying, describing, and comparing representative dairy cattle production system typologies and their interrelation with regional fodder crop production at the European regional scale. This is a necessary step to assess the scope for adapted mitigation and sustainability measures in the future. For this purpose, a multivariate statistical approach is applied. We show how different land-use practices, farm structure characteristics, socio-economic attributes, and emission intensities condition dairy production. Furthermore, the diversity of regional fodder crop production systems is demonstrated by analyzing their distribution in Europe. Together with identified typologies, varying degrees of regional specialization in milk production allow for identifying future strategies associated with the application of integrated systems in key European dairy regions. This study contributes to a better understanding of the existing milk production diversity in Europe and their relationship with regional fodder crop production. In addition, we discuss the benefits of integrated systems as a clear, viable, and resilient alternative to ongoing livestock intensification in the European context. Identifying interactions between components of integrated systems will facilitate decision-making, the design and implementation of measures to mitigate climate change and the promotion of positive socio-economic and environmental interactions.

Key words: Dairy cattle, fodder crops, integrated systems, sustainability and typologies.

1. Introduction

Over the last decades, different initiatives, political bodies, and research institutions have highlighted the role of livestock in the transition towards more sustainable agricultural production (Köchy et al. 2015; Feil et al. 2020; Joint Programming Initiative on Agriculture 2020). Changes in dietary patterns and the reduction of production costs have led to a growing demand in the consumption of animal-based products (Westhoek et al. 2011; Searchinger et al. 2014; Duval et al. 2021). As a substantial part of animal production systems, dairy production significantly contributes to global greenhouse gas (GHG) and nitrogen (N) emissions, as well as to natural resource use (Steinfeld et al. 2006; Gerber et al. 2013; Styles et al. 2018). Despite adverse environmental effects, this sector is key to implementing practices that favor integrated sustainability and providing high quality protein products (Opio et al. 2013; Mehrabi et al. 2020). Hence, identifying, analyzing, and implementing measures that contribute to dairy sustainability, is presented as one of the cornerstones for future actions towards sustainable development of agricultural systems (Animal Task Force 2021). In this context, integrated crop-livestock systems have been described as an alternative to specialized livestock production by potentially contributing to the overall sustainability of agroecosystems (Ryschawy et al. 2012; Sneessens et al. 2019).

Ongoing agricultural intensification can have conflicting effects on the three sustainability pillars (i.e., environmental, economic, and social) (Pretty 2018; Pretty et al. 2018; Rasmussen et al. 2018). Dairy cattle production systems (DPS) are no exception to the intensification trend. Structural changes such as reduced farm numbers, greater specialization, and higher stocking rates can enhance the productivity of DPS while also increasing external input demand resulting in adverse environmental impacts (EIP-AGRI Focus Group 2017; Balaine et al. 2020). Even though recent advances in breeding and feeding management have reduced the overall environmental footprint of the livestock sector, there has been a shift in emissions sources due to a higher dependency on external inputs (del Prado et al. 2021). In this context, main sources of greenhouse gas (GHG) emissions and air pollutants from DPS include enteric fermentation, manure storage, field application (manure and synthetic fertilizers), fossil fuel consumption, and external feed production (Murphy et al. 2017;

Rotz 2018; Sanchis et al. 2019; Amon et al. 2021).While milk production intensification can decrease emission intensity by unit of product of methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), and ammonia (NH_3) (Salou et al. 2017), it can also cause other context-specific social and environmental impacts (Clay et al. 2020). Recently, integrating dairy and fodder crop production scenarios have been suggested as crucial step towards the design of resilient and resource-efficient food production systems of the future (Karlsson and Röös 2019).

DPS rely on concentrates and forage to meet the nutritional needs of animals. More than 50% of the dry matter supplied to bovine animals in the European Union (EU) consists of fodder maize, grass, and other roughage crops, which are mostly locally produced (Karlsson et al. 2021). Inversely, Europe depends at a larger extend on third countries for the supply of protein-rich animal feedstuff (European Commission 2019). Many of the feedstuff used for animal feeding in the EU are imported from the Americas becoming a risk to the sustainability of the sector in the continent (San Martin et al. 2021).This provides opportunities for local fodder crop and livestock production systems, favoring resilient DPS based on short supply chains (Perrin and Martin 2021). Balancing fodder crop production with livestock nutritional needs at the farm level is described as a "win-win" integrated strategy for greater economic and environmental sustainability of agricultural production (Dos Reis et al. 2021). In this context, recoupling crops and livestock offers new opportunities for economic growth, the provision of ecosystems services, and the reduction of negative environmental impacts (Stavi et al. 2016; Garrett et al. 2020; Animal Task Force 2021). Hence, integrated systems favor the creation of synergies between farmers, facilitating not only the exchange of products but also of knowledge in a context of circular economy (Martin et al. 2016; Muscat et al. 2021; Schut et al. 2021).

FIGURE 1

Europe is diverse and complex as far as farming and livestock systems are concerned (Neumann et al. 2009; Guiomar et al. 2018). Different land uses, diet composition, crop species, herd management strategies, and manure management patterns largely determine the characteristics of the dairy-fodder crop production systems in each European region. Thus, a region-specific analysis is needed to assess the sector's challenges (van den Pol-van Dasselaar et al. 2020). More specifically, tailored sustainability strategies require selecting an adequate scale for proposing and implementing measures adapted to specific circumstances and particularities of the different regions. In this regard, the EU provides an administrative classification for the entire territory: the Nomenclature of Territorial Units for Statistics (NUTS) (EUROSTAT 2020). However, official statistics alone are often insufficient or incomplete when applying sustainability measures, due to the lack of detail about structural, socio-economic, and environmental aspects of farms and their interrelationships. Several authors have analyzed typologies of DPS at different European scales from the perspective of structural or economic characteristics (Gonzalez-Mejia et al. 2018; Poczta et al. 2020). Nonetheless, integrated and regional approaches could better assess the sustainability of this systems and thus enable better policies (Acosta-Alba et al. 2012; Arulnathan et al. 2020). Therefore, an adequate assessment of the existing fodder and dairy production system typologies cooperates to a better understanding of their diversity and heterogeneity (Alvarez et al. 2018), opening the door to the implementation of future integrated systems.

Including fodder production in the assessment of DPS typologies is presented as a necessary step to estimate the specific needs and specificities of each region, apply adapted measures, optimize resource use, and reduce negative environmental impacts. Thus, the main objective of this work is to identify and describe representative DPS typologies and account their connection with selected fodder crop production systems at the European NUTS2 scale. In addition, this work evaluates the limitations of current databases for the characterization of different dairy and fodder crop production typologies across European regions. The proposed typology analysis will facilitate informed decisions when selecting mitigation and sustainability measures through a better understanding of the sector's diversity at the regional scale.

2. Material and methods

First, a framework of indicators was selected to describe the dairy cattle-fodder crop production systems at NUTS2 regional scale. These include specific indicators for DPS, fodder crop production, and emission intensities. Second, a multivariate statistical approach was applied.

2.1 Dairy and fodder production indicators

Indicators related to physical characteristics, economic performance and emissions have been commonly used for the determination of farm typologies (Gonzalez-Mejia et al. 2018; Bánkuti et al. 2020; Kihoro et al. 2021). Therefore, a framework of indicators was built for the identification of the existing DPS typologies based on their structural, land use, socio-economic, and emission intensity characteristics. The boundaries of the analysis were the farm itself, discarding all possible indicators describing off-farm impacts or characteristics. Consequently, a set of 11 indicators was selected for this analysis (Table 1). The results of the Farm Structure Survey (FSS) were used as data source for populating the indicators (EUROSTAT 2013a). Specific data for DPS was obtained by selecting the “FT45-specialist dairying” farm category. All European NUTS2 regions were initially eligible for the analysis. Data from 2013 was used since it was the most recent set with complete records for all the regions considered.

TABLE 1

In addition, the percentage (%) of utilized agricultural area (UAA) associated with specialized dairy farms over the total UAA of each region was calculated to assess the degree of regional specialization for dairy production (EUROSTAT 2019). For this purpose, the following equation was used (Eq. 1):

$$SP_{dairy} = \frac{UAA_{dairy}}{UAA_{total}} \times 100 \qquad (1)$$

Where SP_{dairy} represents the percentage (%) of UAA associated with dairy specialist farms over the total UAA of each the region, UAA_{dairy} is the UAA associated with dairy farms per region (ha) and UAA_{total} represent the total UAA available in each region (ha).

DPS typologies were also identified and described using two emission indicators: i) intensity of total GHG and ii) intensity of ammonia (NH_3) emissions (Table 1). Intensity of total GHG emissions was estimated by means of the 2013 National Inventory Reports (NIR) (European Environmental Agency 2022). The following most representative direct farm-level GHG emission categories from DPS were assessed: i) CH_4 emissions from enteric fermentation, ii) CH_4 emissions from manure management, and iii) direct N_2O emissions from manure management. Due to the lack of specific data at the European NUTS2 scale, a three-fold approach was followed for their estimation: i) total national emissions were determined for each GHG category through the NIR, ii) the share of livestock units (LU) for "specialist dairying" category in the region over the total national population was used to calculate regional emissions, and iii) the raw milk production per NUTS2 was used for the estimation of emission intensity per region for each GHG. Data for the year 2013 was used for populating this indicator. The following equation was used (Eq. 2):

$$E_{reg} = \frac{(GHG_{total} \times POP_{reg})}{Milk} \qquad (2)$$

Where E_{reg} is the emission intensity per unit of product for each one of the GHG at a NUTS2 scale ($kgCO_{2eq}$ $kg\ milk^{-1}$), GHG_{total} are the total national emissions for dairy cattle for each GHG category ($kgCO_{2eq}$), POP_{reg} is the share of livestock units (LU) for the "specialist dairying" category in the region over the total national dairy cattle population, and the $Milk$ is the total regional raw milk production (kg of raw milk). Total regional GHG emissions were obtained by adding all individual emissions of each of the gases estimated (Eq. 3):

$$\sum GHG = E_{CH4_{ent}} + E_{CH4_{man}} + E_{N20_{man}} \qquad (3)$$

Where $\sum GHG$ is the total GHG emission intensity of milk production ($kgCO_{2eq}$ kg^{-1}), $E_{CH4_{ent}}$ are the CH_4 emissions from enteric fermentation ($kgCO_{2eq}$ kg^{-1}), $E_{CH4_{man}}$ are the CH_4 emissions from manure management ($kgCO_{2eq}$ kg^{-1}) and $E_{N20_{man}}$ are the direct N_2O emissions from manure management ($kgCO_{2eq}$ kg^{-1}). Individual GHG emissions for CH_4 and N_2O were converted to CO_{2eq} using the Global Warming Potential (GWP100) for the year 2021 (IPCC 2021). GWP values of 27.2 and 273 were used for the CH_4 and N_2O respectively.

In order to estimate the intensity of NH_3 emissions from manure management, national emissions were retrieved from the data reported on the 2013 Informative Inventory Reports (IIR) in the context of the Convention on Long Range Transboundary Air Pollution (CLRTAP) (European Environmental Agency 2022).

Share of livestock units (LU) for "specialist dairying" category in the region over the total national dairy cattle population and raw milk production per NUTS2 were used for the estimation of emission intensity per region. Data for the year 2013 was used for populating this indicator. The following equation was used (Eq. 4):

$$NH_{3total} = \frac{(NH_{3man} \times POP_{reg})}{Milk} \qquad (4)$$

Where NH_{3total} is the regional NH_3 emission intensity per unit of product, NH_{3man} accounts for the national NH_3 emissions derived from manure management (housing and storage) excluding reactive N emissions from grazing or manure application to soils, POP_{reg} is the share of livestock units (LU) for the "specialist dairying" category in the region over the total national dairy cattle population, and *Milk* is the total regional raw milk production per year (kg of raw milk year^{-1}) for each NUTS2 region.

Regarding the fodder production indicators, these crops are defined as the ones that are intended primarily as animal feed. Fodder crops are divided into temporary or permanent according to their management and harvest patterns (FAO 1994). Permanent crops are associated with the same land for more than five years. In this regard, the EU statistics considers fodder roots, brassicas, temporary grasslands, green maize and legumes as temporary fodder crops, and permanent meadows and grasslands as permanent fodder crops (EUROSTAT 2013b).

In order to analyze the different patterns of fodder crop production at the European regional level, a database with the areas occupied by selected fodder crop categories (temporary grasslands, leguminous crops, green maize, and permanent grasslands) for each of the NUTS2 regions was created (Supplementary material 1). The FSS for the year 2013 was used as the data source for populating all the 4 indicators selected (Table 1). The ratio of each crop over the total UAA of the region was calculated to determine the predominance of one or another crop category in the region.

DPS and fodder crop production datasets can be found in Supplementary Material 1. All the retrieved national GHG and NH_3 emissions are provided in the Supplementary Material 2.

2.3 Data analysis

Identification of existing DPS clusters was carried out following a three-step multivariate statistical approach: i) principal component analysis (PCA), ii) K-means clustering and iii) cluster description and comparison. For the identification of existing fodder crop production clusters, a two-fold approach was applied: i) K-means clustering, and ii) cluster description and comparison. PCA analysis was not applied in this second clustering process due to the lower dimensionality of the data. Similar multivariate approaches have been described as a useful procedures for identifying farm typologies (Madry et al. 2013; Robert et al. 2017; Sinha et al. 2021)

NUTS2 regions with incomplete data were excluded from the DPS typology analysis and subsequently from the fodder crops database. Then, the data was standardized. Of the 283 regions initially included in the analysis, 32 were excluded (11.3%) based on the criteria of data completeness. The data was analyzed using the R statistical software (R Core Team 2021). Identified DPS and fodder crop production clusters were spatially represented using geographic information systems by means of the QGIS software (version 3.16) (QGIS Development Team 2021).

2.3.1 Principal Component Analysis (PCA)

In order to analyze the existing interrelationships between DPS indicators, and thus reduce the number of variables used in successive steps, a PCA analysis was carried out. New linear combinations were calculated from existing indicators, cumulating the variability of the data in a reduced number of principal components (PC). This analysis also enables to assess the contribution of each of the original indicator to the obtained PC.

Before performing the PCA, a correlation matrix of all DPS indicators was computed, in order to identify the level of correlation between the indicators in the dataset. Of those indicators that were highly correlated ($r<-0.85$ or $r>0.85$), only one of each pair was retained. The “Corrplot” package of R was used to visualize the correlation matrix (Wei and Simko 2017). The suitability of the sample size for this statistical procedure was determined using the Kaiser-Meyer-Olkin (KMO) measure. In addition, Bartlett's test of sphericity (Bartlett 1951) was applied to check if the correlation matrix was an identity matrix. Both functions are included in the R “Psych” package (Revelle 2020). The “prcomp” function was used to build the PC. A number of PC whose cumulative variance was over 70% (Rea and Rea 2016) of the total variance was retained. Rotation of the eigenvectors of the respective PC was computed with the objective of analyzing the contribution of each indicator to each PC (<-0.4 and >0.4). The “Factoextra” (Kassambara and Mundt 2020) package was used to visualize the results of the analysis.

2.3.2 Cluster analysis

The optimal cluster number was determined using “NbClust” package (Charrad et al. 2014). By computing 30 different indexes, optimal number of clusters in a dataset is determined. The function was adjusted for the k-means clustering method, setting the minimum cluster number to 2 and the maximum number to 10. The retained principal components were used as input in the clustering procedure. Once the optimal cluster number was identified, the “kmeans” function was used to allocate the different NUTS2 regions into the previously identified clusters.

2.3.3 Cluster description and comparison

The characterization and comparison between clusters was performed using two non-parametric statistical procedures. First, the Kruskal-Wallis test, by means of the “kruskal.test” function, was used to assess the significant differences across clusters. The *chi2* statistic was computed as a factor for determining the sum of the squared deviations among clusters. Second, the Wilcoxon rank sum test, by means of the “pairwise.wilcox.test” function, was then performed in order to calculate pairwise comparisons between clusters. The p-values were adjusted by means of the Benjamin and Hochberg method (Benjamin and Hochberg 1995).

3. Results and discussion

3.1 Results

3.1.1 DPS typologies

High positive correlation was found between the indicators "Average animal number per farm" and "Average farm size by total UAA", and between “Average emission intensity of total GHG” and “Average emission intensity of NH_3 from manure management”. In addition, high negative correlation was found between "Average share of arable land over the total UAA per farm" and "Average share of permanent grasslands over the total UAA per farm". In all cases, the latter indicator was retained. The results for both KMO and Barlett’s sphericity tests show that the database is appropriate for the following statistical analysis.

The PCA found that the first four PC cumulate 78.7% of the variance. More precisely, PC1 accounts for 35.7% of the variance, while PC2, PC3 and PC4 described 18.6, 13.3, and 11.1% of the variance, respectively. To assess the contributions of each indicator to the PC computed, the weight of the corresponding eigenvectors was analyzed through the rotation value of their components. The standard deviation, percentage variance, percentage cumulative variance and rotated value of the selected components can be found in the Supplementary material 3.

The first PC brings together those indicators that describe the productivity and farm size by means of the milk production ("Average milk yield per cow"), farm size (“Average animal number per farm”) and total workforce (“Average workforce per farm”). The second PC describes the emission intensity by means of the indicator “Average emission intensity of total GHG” and the livestock density expressed by the “Average livestock density over total UAA per farm”. Farm tenure is represented by PC3, given the high contributions of the indicator "Average share of owned land over rented land" to this component. Finally, the prominence of arable crops over permanent grassland at the farm level is represented by PC4, which has a large contribution from the indicator "Average share of arable land over the total UAA per farm".

The scores of the first four PC were used to determine the different DPS clusters. According to the results of the "NbClust" function, a significant number of analyzed indices indicated that the optimal cluster number was 4. Each of the formed clusters had different contributions from the four retained PC, thereby allowing for their characterization and comparison. Analyzed NUTS2 regions were allocated to one of the identified clusters. The mean value and standard deviation for each indicator, including those not used for the clustering analysis, are shown by cluster in Table 2. In addition, statistically significant differences were found between the clusters for all the variables analyzed.

TABLE 2

The results presented in Table 2 reveal the diversity of DPS when analyzing the considered characteristics. The largest farm size, in terms of both dairy animal numbers and UAA per farm, can be observed in Clusters 1 (CL1) and 2 (CL2). Likewise, the productivity observed in both clusters is substantially higher than in Clusters 3 (CL3) and 4 (CL4) with lower emission intensities for both GHG and NH_3. Although CL2 represents larger and more productive farms than those in CL1, both clusters present land uses predominantly directed to arable crop production, with a lower share of permanent grasslands. The average number of workers is inversely proportional to the share of family labor. This is observed in CL1 and CL2, which have a higher number of total workers and fewer family laborers compared to CL3 and CL4. As can be seen in Figure 3, the geographical distribution of NUTS2 regions included in CL1 is very heterogeneous, with a notable presence in Spain, France, Denmark, Hungary, the United Kingdom, Norway, Sweden, Finland, and Flanders in Belgium. CL2 is mainly concentrated in Eastern Germany, the Czech Republic, and Estonia.

Likewise, a greater presence of permanent grasslands relative to arable crops is observed for CL3 and CL4. In the case of CL4, significantly higher values are observed for family labor, GHG and NH_3 emission intensity, the number of animals per hectare of UAA, and the share of owned land. As for CL3, a highly heterogeneous geographical distribution is observed. This type of DPS is representative of all regions of Ireland, Poland, Lithuania, Latvia, Austria, Croatia, or Bulgaria. Likewise, the Atlantic coast of Spain, the west coast and the central regions of the United Kingdom, the Mediterranean coast of France, and most of the Netherlands are represented by this cluster. CL4 is the most represented in Romania and Greece, and it is the least geographically representative cluster in Europe.

Concerning the ratio of UAA used by specialized dairy farms over the total UAA available in each region, the results show unequal levels of specialization across Europe in terms of land use (Figure 2). Higher levels of specialization are observed in regions of the Netherlands, southern Germany, western-southern France, eastern Poland, Sweden, and Finland. Likewise, the southern (Spain, Italy, Portugal, and Greece) and eastern (Romania, Bulgaria, and Hungary) European NUTS2 regions show lower specialization values.

FIGURE 2

3.1.2 Fodder crop production typologies

Regarding the fodder crop production typologies, no highly significant correlation was found between any of the indicators included (r<-0.85 or r>0.85). After standardization of the observations, the results obtained from the "NbClust" function indicated that 5 was the optimal cluster number. Each of the formed clusters has different contributions from the different crops analyzed, allowing for the characterization and comparison of the clusters based on the relevance of the assessed crops per region. The mean value and standard deviation for each indicator, are shown by cluster in Table 3. In addition, statistically significant differences were found between the clusters for all the variables analyzed.

TABLE 3

The results revealed a heterogeneous distribution of the analyzed crops among the different NUTS2 regions (Table 3). Within Cluster 1 (CCL1) regions, 50% of the total available UAA is dedicated to cultivating temporary grasslands, 16% to permanent grasslands, and <1% to green maize. This cluster comprises regions from Norway, Sweden, and Finland (Figure 3). Moreover, both Clusters 1 (CCL2) and 2 (CCL2) present a clear predominance of one of the fodder crops analyzed. In the case of CCL2, 70% of the available UAA is occupied by permanent grasslands, followed to a lower extent by temporary grassland (6%), green maize (2%), and leguminous fodder crops (<1%). This cluster is mainly located in Ireland, the United Kingdom, and some Atlantic regions of the Iberian Peninsula and the Mediterranean (Figure 3).

Regarding the CCL3, 24% of the available UAA is occupied by permanent grasslands, followed by temporary grasslands (5%), green maize (3%), and leguminous fodder crops (<1%). This cluster is evenly distributed across Europe (Figure 2). Cluster 4 (CCL4) is characterized by having 28% of its UAA intended for permanent grasslands, 16% to green maize, 8% to temporary grasslands, and less than 1% to leguminous fodder crops. Regions included in this CCL4 are concentrated in western France, Belgium, the Netherlands, Denmark, and northeast Germany. Furthermore, the NUTS2 regions of Central and Eastern Europe are primarily included in cluster 5 (CCL5), where 27% of the area is occupied by permanent grasslands, 4% by green maize, 4% by leguminous fodder crops, and 1% by temporary pasture.

Overall, the results reveal different levels of specialization at the NUTS2 regional scale with regard to the production of fodder crops. In the case of CCL1, CCL2, and CCL4, more than half of the available UAA is destined to fodder crop production, obtaining values of 67, 79, and 53%, respectively. A lower presence of the analyzed crops is observed in CCL3 and CCL4 with 40 and 37% values.

3.2 Discussion

3.2.1 Integrated assessment of key dairy-fodder crop production systems

To date, previous studies have highlighted the need to move towards more sustainable farming systems across the three sustainability pillars (Duval et al. 2021; Helfenstein et al. 2022). In this sense, livestock production in high-and middle income countries is experiencing a transition towards more intense, concentrated, and productive systems (Britt et al. 2018). This intensification has clear effects on the environmental sustainability in these regions, and may affect less intensive systems in other parts of the world in similar ways in the future (Curien et al. 2021; Munidasa et al. 2021). Identifying the diversity of livestock systems such as DPS together with their interactions with fodder crops would allow to better address these impacts in an adapted manner. Furthermore, by promoting the relationship between crop production and livestock farming, feeding and fertilizer needs could be satisfied (Jouan et al. 2020). The results obtained in this study cooperate in this regard by showing how different productive systems and land uses interrelate with fodder crops in Europe, enabling the application of regionally-tailored measures to promote integrated sustainability.

FIGURE 3

Although there is currently no individual indicator that analyzes the degree of specialization in milk production of European NUTS2 regions, concrete proxies can be used to assess it. By analyzing the share of total UAA dedicated to dairy cattle specialist farms, the degree of regional specialization can be inferred, thus allowing for the identification of those regions where DPS play a more relevant role in the territory. As shown in Table 4, among the DPS clusters identified, CL3 shows the highest specialization of its UAA. In this case, 21% of the UAA is oriented to milk production, with maximum values of 75% in some regions. In the case of CL1 and CL2, the average values of UAA specialization are 13 and 10%, respectively. The lowest average specialization values were found in CL4, with an average of 2% of the UAA oriented to DPS. . As the most specialized cluster for dairy production, CL3 largely overlaps with fodder crop production systems where permanent grasslands are the main fodder source (CCL2) (Supplementary Material 4). Moreover, the clusters (CCL3) where additional fodder sources such as temporary grasslands, green maize and leguminous crops are present could also be found in CL3. Unlike temporary grasslands, predominant in CCL1, permanent grasslands have been associated with less intensive management practices such as lower inputs of manure and fertilizer, grazing pressure, tillage frequency, and grassland showing renewal (Lesschen et al. 2016). As mentioned by other authors, it is vital to point out the existing differences in the provision of ecosystem services and multifunctionality between permanent and temporary grasslands (Schils et al. 2022). Although the productivity of temporary grasslands is substantially higher than that of permanent ones, the intensive management applied (e.g. fertilizers and tillage) could reduce their natural value (Reheul et al. 2007). In this regard, preserving these permanent grasslands could have positive long-term effects in ensuring their productivity and favoring the provision of ecosystem services (Qi et al. 2018; Dumont et al. 2019), thus enhancing the potential for climate change mitigation.

TABLE 4

Regions included in CL1, showed an average of 12.8% of dairy-oriented agricultural land over the total available UAA (Table 4). These DPS are characterized by more intensive systems than those found in other clusters, observing high levels of milk production, medium farm sizes, and greater presence of surface area oriented to arable land. In terms of, fodder crops, 48.1% of the regions gathered in CL1 overlap with CCL3, which does not show any predominance among the crops under study. In addition, a presence of green maize, represented by CCL4, can be observed in 17.2% of the regions included in CL1. The observed link between farming intensity, low presence of grasslands and cultivation of green maize could indicate of higher silage and concentrate supply (Leiber et al. 2017). While this type of farm management may be associated with lower emission intensities (Bava et al. 2014; Jayasundara et al. 2019), the large use of concentrates, mostly based on cereals and other human-edible feeds, highlights food-feed competition (Ertl et al. 2015). It can also lead to an increase of indirect emissions from off-farm feed production and fossil fuel consumption (Guerci et al. 2013). In this context, reducing the dependence on commercial concentrates could foster the transition towards farming systems which rely more heavily on locally produced inputs, maximizing the utilization of farm-grown crops (Horn et al. 2014). In this way, synergies between farmers could be facilitated, thereby enabling the interrelationships between the different components of the agrological production and promoting agroecological principles (Bonaudo et al. 2014; Wezel et al. 2020).

Lower levels of regional specialization could be observed in CL2 and CL4 with 9.8 and 2.1% of the total available UAA oriented to milk production, respectively (Table 4). Regarding the distribution of fodder crops in the clusters, large areas of these regions overlap with CCL3 (i.e., 41.2% for the CL2 and 46.2% for CL4) (Supplementary material 4), which suggests that are largely occupied by crops not included in this study. In this regard, high milk yields and farm sizes observed in CL2 could be associated with a larger presence of crops potentially included in the animal diet such as cereals, leguminous or other non-fodder crops. As shown in Table 2, the DPS described by CL4 are characterized by small family-owned, low performance farms. Although these DPS typology presents several challenges for the future, mainly due low profitability (Markova-Nenova and Wätzold 2018), there is also potential for applying measures to increase their sustainability by favoring self-consumption of inputs and promoting a higher degree of agro-biodiversity (Guarín et al. 2020) .33.3% of these regions are characterized by the presence of leguminous crops (CCL5) (Supplementary Material 4). Cultivating these crops, as a source of protein for animals, would positively affect nitrogen fixation while reducing the economic dependence on external inputs (Peyraud and Macleod 2020; Ditzler et al. 2021). In this regard, multiple authors have highlighted the additional difficulties associated with leguminous crops compared to others (such as green maize) mainly during the conservation process (Peyraud et al. 2009; Tabacco et al. 2018). However, they can contribute to the economic sustainability of less industrialized DPS by providing protein-rich feed sources, reducing the need for external feeds. Maximization of profit per unit of product is presented as a fundamental factor of the financial drivers that condition the succession and expansion of dairy farms (Hayden et al. 2021). Hence, the application of integrated dairy-fodder systems, could ensure their continuity through the application of more sustainable and resilient farming practices (Shadbolt et al. 2017).

In addition, the results obtained from this combined analysis allow for the identification of regions where the link between key dairy cattle and fodder crop production systems is more likely to occur (Figure 4). Interconnections between DPS and fodder crops are remarkable in the Netherlands, Germany, Belgium, and southern Denmark. The observed higher dairy specialization of the UAA indicates a strong bond between these systems accompanied by a notable presence of green maize (CCL4) among the fodder crops analyzed. However, differences in the farm structure between the eastern parts of Germany (CL2) and other regions of the Netherlands, Germany, Belgium and Denmark (CL1), indicate unequal sectorial development, notably due to different production backgrounds (e.g. state-owned farms). Similarly, evident interrelations between fodder crops and DPS are observed in north-western France. In this case, intensive medium size farms (CL1) with a strong presence of UAA oriented to DPS and a remarkable presence of green maize are found (CCL4). Concerning the presence of different grassland typologies, their distribution varies across the different DPS identified. In this respect, the Scandinavian regions are characterized by high levels of specialization and a prevalence of intensive farming systems (CL1) where temporary grasslands are predominant (CCL1). Permanent and temporary grassland are distributed across the Atlantic regions of Spain, Ireland, western UK, and Croatia where the role of this fodder crop category is fundamental (CCL2) in supporting more extensive DPS systems (CL3). This connection is also noticeable in some alpine regions of Austria and Slovenia, where similar DPS (CL3) rely to a large extent on permanent grasslands (CCL2), probably due to the climatic and biophysical characteristics of these regions. Lastly, the low levels of specialization observed in some Eastern Europe regions are accompanied by a clear presence of leguminous crops (CCL5) where small, family-owned, low productive, and high emission intensity farms (CL4) are found.

FIGURE 4

3.2.2 Future prospects

Interconnected crop-livestock systems are presented as more resilient systems than highly specialized DPS, due to the implementation of practices such as input reduction, resource conservation, or ecosystem services provision (Shadbolt et al. 2017; Stark et al. 2018; Wezel et al. 2020). European initiatives such as the "Farm to Fork" strategy open the door to strengthening synergies between DPS and fodder crop production, which would be beneficial from the perspective of all three sustainability pillars (European Commission 2020). In this sense, previous authors have identified multiple climate change mitigation and adaptation measures oriented to integrated systems whose application favors the reduction of the overall environmental impact of DPS (Buller et al. 2015; De Souza Filho et al. 2019; Boeraeve et al. 2020). DPS are widely associated with significant nutrient losses at the farm scale (Dentler et al. 2020). In this respect, synergies between dairy and crop production could be enhanced in the context of circular systems by improving manure storage and application practices and techniques (Bosch-Serra et al. 2020). Likewise, integrated systems where farm-grown protein crops play a more significant role could represent "win-win" strategies from both economic and environmental standpoints, allowing strong interactions between farmers (Catarino et al. 2021). In addition, better conservation of biotic and abiotic resources by optimizing and adapting integrated practices, such as grazing, could better mitigate the environmental impact of the livestock activity (Teague et al. 2011; Ravetto Enri et al. 2017; Díaz de Otálora et al. 2021; Senga Kiessé et al. 2022).

Given the large diversity of European DPS demonstrated in this study, there is no “one-fits-all” solution to mitigate these environmental impacts at a continental scale. In line with the initial hypothesis of this work, the diversity of existing systems in Europe could allow the application of specific measures for each region, favoring adapted strategies oriented to resilient and sustainable DPS. Moving from existing linear production patterns onto integrated systems based on better resource management and the implementation of circular economy principles could cooperate in this regard (Duru and Therond 2015). Furthermore, better understanding of the different sociological aspects of farming activity could enable future policy interventions oriented to sustainability challenges (Bartkowski et al. 2022). Moreover, adaptation to new economic, social, and environmental contexts is essential when designing and securing future food systems. The analysis of existing databases allows us to identify areas for improvement and reaffirm the need to expand the scope of the current data collection schemes to cover aspects related to environmental and social sustainability.

4. Conclusions

The proposed typology analysis follows an innovative approach that allows different stakeholders to obtain a more comprehensive view of dairy cattle-fodder crop production systems at a European regional scale. This study sets the base for the identification and application of holistic and adapted concepts to create more sustainable and resilient DPS at a regional scale. Hence, the results of this study have direct practical implications and can facilitate informed decision-making regarding the integrated sustainability of dairy cattle-fodder production systems in Europe.

Furthermore, knowledge gaps, mainly concerning specific indicators for the assessment of the relationship between fodder crops and DPS, the level of regional specialization in different livestock activities, and the intensity of emissions specific to each production type and region, were identified and overcome. Further research is needed to integrate into the analysis farm-level data on diets, crop allocation and circularity in the context of dairy cattle-fodder production systems. Future database improvements should reflect more specific indicators, and cooperate in the development and implementation of the integrated dairy-crop production systems. Notably, accounting for intra-national specificities such as feeding regimes and management in GHG and air pollutant inventories, will allow for a better analysis of DPS environmental impacts. In this context, future studies should focus on addressing these interactions at a lower regional breakdown scale (NUTS3), facilitating even more adapted measures.

Declarations

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