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Context:

EU accounts for 32% of the world's milk production, thereby ranking as the largest producer among the global regions (Segerkvist et al., 2020). With annual emissions of 195 Tg CO_2-eq, the dairy sector is also the highest agricultural greenhouse gas (GHG) contributor within the EU-27 (Lesschen et al., 2011). Over the past decade, growing awareness of environmental problems associated with livestock production, volatility in farm incomes, and animal welfare concerns have reinforced the need for sustainable food production systems. In this context, European dairy production faces many challenges related to environmental, economic, and social dimensions of sustainability, with particular regard for the need to assess and eventually mitigate GHG emissions. Therefore, holistic assessment tools are required to inform how best to achieve greater sustainability across the three dimensions. To meet this requirement, the objective of the Milkey project was to develop a whole system approach to identify optimal GHG mitigation strategies in dairy production systems (DPS) based on a multi-criteria sustainability assessment (MCA).

Methods:

The MCA was conducted within the DEXi framework (Bohanec, 2020). DEXi is a software program that deals with multi-attribute decision-making. From an expert perspective, it associates a hierarchical decision model based on qualitative attributes. These attributes are organized in a tree structure allowing to build dependencies between attributes of different levels. Each decision is represented by a set of attributes, where the attributes of the first level are assessed individually and then aggregated into increasingly comprehensive levels. The attribute values are discrete and expressed with qualitative statements such as "low, medium, or high" determined through a scaling procedure (Craheix et al., 2015). The first step of the model development was to define attributes organized in principles, criteria, and indicators (PCI) for each sustainability dimension (environmental, economic, and social) in separate working groups. The choice of PCI was guided by three objectives, i.e., i) to best describe the main challenges faced by European dairy production systems (DPS), ii) to point out synergies and trade-offs across sustainability aspects, and iii) to help identify GHG mitigation strategies at the farm level. The second step was to define qualitative scales for each PCI element, as well as utility functions that aggregate each level of the tree. At each node, the upper-level score was calculated based on weighting factors attributed to each PCI element from the lower level. The weighting factors were provided as a result of a consensus between the project's partners, throughout several participative workshops. Finally, a list of data requirements was developed based on selected indicators to guide the data collection in case study farms, and, test the model with real data.

In the environmental dimension, we selected 22 indicators grouped into 4 principles: best dairy herd management practices, environmental quality, abiotic resources conservation, and biodiversity conservation. Five of the indicators were derived from LCA impact categories (i.e., climate change potential, eutrophication potential, acidification potential, heavy metal balance, and cumulative energy demand) (Figure 1). Thus, an LCA at the farm scale was performed using the Simapro 9.3.0.3 software. ILCD 2011 Midpoints indicators (for climate change and water resource depletion), CML-IA baseline v3.05 (for eutrophication and acidification), and CED 1.11 (for total energy demand) (Frischknecht et al., 2015), as implemented in Simapro software were used for the calculation of impact categories. Moreover, we used the data requirements suggested by the MEANS IN-OUT online platform to conduct the LCI of dairy production systems (Auberger et al., 2018).The functional unit was 1 kg of fat-protein-corrected milk (FPCM). The background data came from the Ecoalim database (Wilfart et al., 2016) for feed ingredients, from the Agribalyse database® for agricultural operations, machinery, and inputs, and from ecoinvent v3.8 for other background data (national energy mix and infrastructure). Emissions calculations were based on guidelines proposed by Koch and Salou (2015), with emission factors adapted for each country if relevant. The nitrates leaching were calculated according to the INDIGO® method and the RUSLE model. Then, the quantitative results obtained by the LCA were transformed into qualitative scores from "low" to "high". Such scores were determined based on reference values from the milk production-LCA literature.

Data were collected by 10 case study farms selected to represent DPS in key European regions throughout France, Germany, Greece, Ireland, Norway, and Poland. In this article, we chose to present only 3 case studies from France, Ireland, and Germany (Table 1).

Results:
Following the MCA approach, we designed an assessment tree for European DPS while considering the three sustainability dimensions. Figure 1 presents the indicators, criteria and principles of the environmental branch with the weights attributed to aggregated PCI elements. Table 2 indicates the environmental impacts of each case study expressed per kg of FPCM at the farm scale. The Irish DPS has lower environmental impacts compared to German and French DPS despite its higher number of dairy cows and its lower average milk production per cow (5362 L). While the French system had a high level of milk produced per cow (around 9567L), it had the highest impacts for all indicators under study except for climate change. In terms of environmental sustainability (figure 2a), the Irish system gets a "medium to high" score, with performance varying across PCIs. For instance, the Irish system scored very high for air quality, medium to high for energy use, climate change, water quality, and circular feed supply; and low for biodiversity and quantity of unproductive cattle. The German system also got a medium to high score for the overall environmental sustainability. It scored "medium to low" for feed efficiency, energy use, and biodiversity ("medium to low"), which constituted its lowest performance. The French system achieved an overall "medium" score since the majority of its middle scores are between medium to low and medium to high. Finally, when considering performance across the three sustainability dimension, the French and German systems showed the same level of economic sustainability ("medium to high") and scored higher than the Irish system ("medium") (figure 2b). Nevertheless, in terms of social sustainability, the Irish system achieved a high score whereas the French and German systems scored "medium" and "medium to high", respectively.

Discussion:

The DEXi approach is a semi-quantitative method combining parameters from various sources. In the environmental branch, this study notably included LCA results or LCI parameters. DEXi allows to compare environmental, social and economic issues to the same level. Specifically, it allows for the identification of a diversity of synergies and trade-offs within and across sustainability aspects on case study farms, notably when implementing GHG mitigation strategies. It has the potential to form a common basis to compare heterogeneous dairy production systems in Europe. The wide range of existing farming conditions (e.g., climate, technological advancement, farm size, economic performance, farming tradition) also influences the results and may have repercussions in the uptake and suitability of mitigation strategies. Overall, this multi-criteria sustainability assessment establishes a solid basis to use and compare data from case study farms and could increasingly inform experts and non-experts about sustainable dairy production systems.

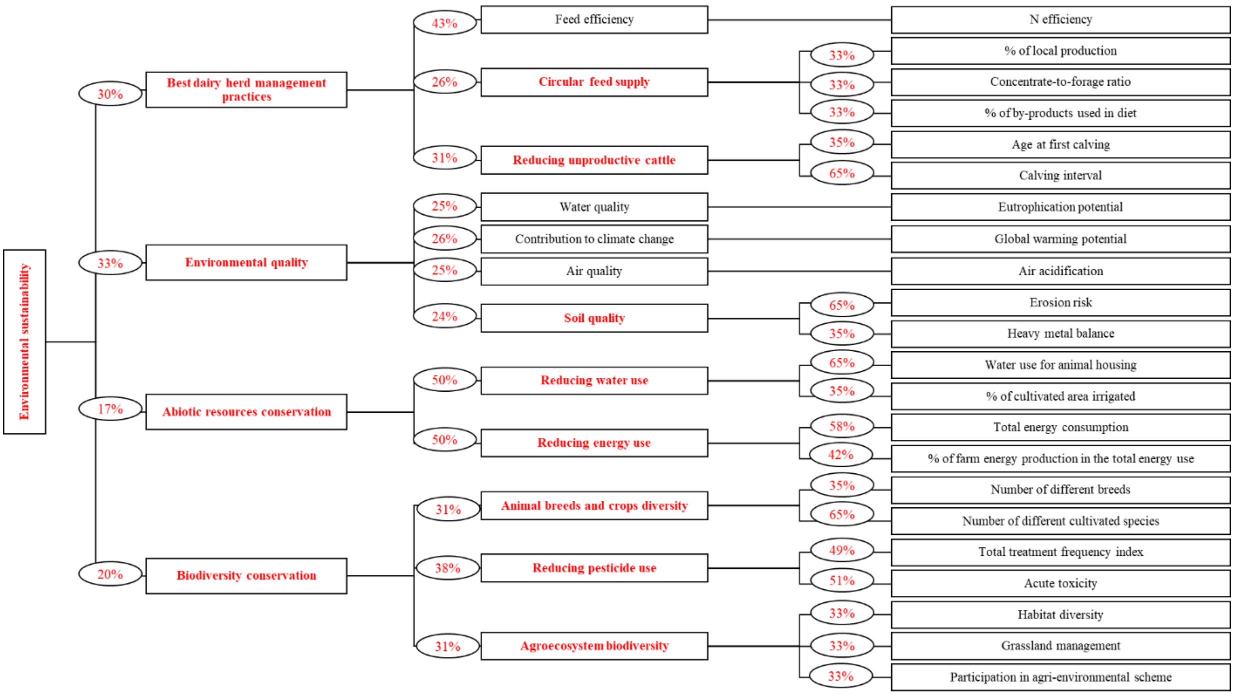

Figure 1: Weight attribution of the environmental DEXi tree. Red boxes correspond to the aggregated criteria, principles, and dimensions, while black boxes are directly dependent on corresponding indicator values.

Table 1: Characteristics of studied dairy production systems (DPS) in France, Ireland and Germany

	French DPS	Irish DPS	German DPS
Dairy herd size (cows)	75	185	110
Utilised agricultural area (UAA, ha)	103.5	87	230
Total milk production (L)	717511	991996	784000
Milk/cow (L)	9567	5362	7127
Length of grazing season (days)	168	304	214

Table 2: Environmental impacts calculated by LCA for 3 contrasted dairy production systems. The results are expressed per kg of FPCM at the farm scale

	French DPS	Irish DPS	German DPS
Climate change (kg CO_2 eq/kg)	1.35	1.14	1.46
Eutrophication (kg PO_4^{3-} eq/kg)	0.0059	0.0034	0.0046

Acidification (kg SO_2 eq/kg)	0.0126	0.0084	0.0088
Total energy use (MJ/kg)	3.84	1.87	2.40
Heavy metal balance (mg/ha)	0.0059	0.0032	-0.0032

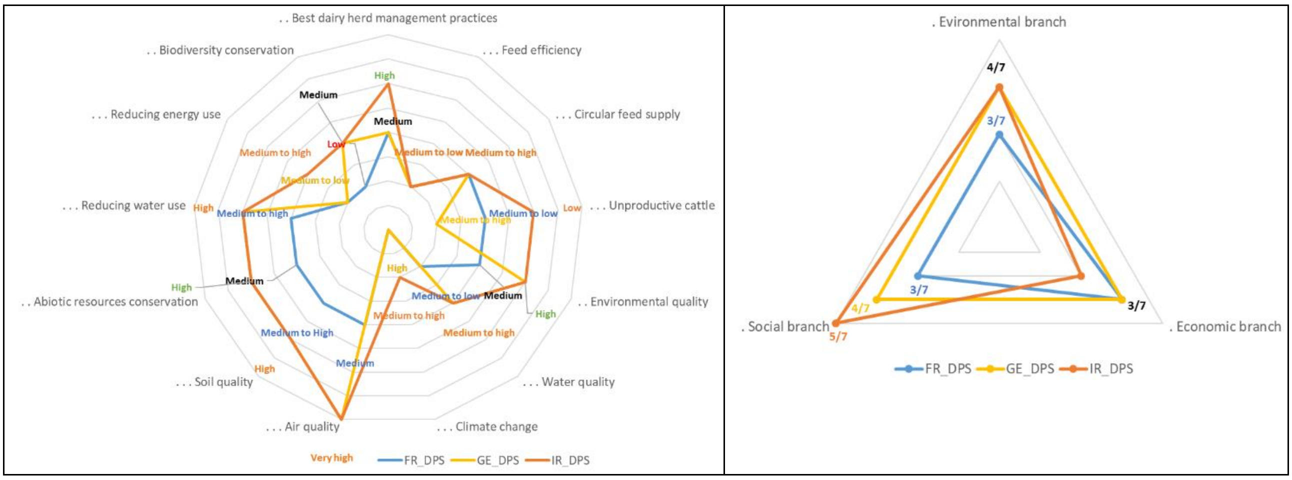

Figure 2: Sustainability scores for a) the environmental branch b) the overall sustainability score for the 3 case studies**.**

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