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**Sustainability assessment of key European dairy cattle  
production systems: System identification, analysis, and  
greenhouse gas and nitrogen emission mitigation**

Ph. D. Thesis by

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## **Abstract**

Dairy cattle production systems (DPS) are part of the backbone of the European agricultural sector. However, during the last decades, multiple challenges have put their environmental, economic, and social sustainability at risk. In this regard, reducing their impact, ensuring their economic profitability, and safeguarding their contribution to society are vital aspects that need to be addressed by the scientific community and policy action. In this context, the lack of adequate concepts, tools, and approaches is still a limiting factor when studying the integrated sustainability of DPS. To this end, this Ph.D. Thesis tackles some of the sector's main challenges in terms of sustainability by developing concepts, methodologies, and strategies adapted to the particular needs of a wide range of European DPS. Throughout four interconnected chapters, better and more targeted decision-making based on scientific knowledge is facilitated. In particular, special emphasis is placed on evaluating the tools for sustainability assessments, the analysis and clustering of the diversity of existing production systems, and the adapted mitigation of greenhouse gas (GHG) emissions and nitrogen (N) losses at the farm scale.

As for the evaluation of tools for integrated sustainability assessment, this Ph.D. Thesis presents a quantitative framework that comprehensively evaluates whole-farm tools and models. On average, the models covered 40% of the total assessed indicators. The obtained results show how the models considered incorporate more indicators from the environmental pillar than those related to the economic or social sphere. In addition, this work facilitates the identification of avenues for future model developments, allowing for a more complete and detailed assessment of sustainability. Thus, this framework is presented as an effective approach that allows potential users to make knowledge-based decisions when choosing the best tools for their needs.

The results obtained from the analysis of the diversity of DPS, allow for the identification, description, and clustering of European regions according to different typologies of production systems. In addition, this Ph.D. Thesis evaluates the dairy-fodder crop interactions across Europe. The 16 representative typologies identified combine DPS's structural, productive, socio-economic, and environmental characteristics with the level of overlap with the most relevant fodder for dairy production across 251 NUTS2 regions. Together with these typologies, the different degrees of regional specialization for dairy production allows identifying future targeted strategies for mixed farming systems (crop-livestock) by implementing integrated production systems across European regions. Furthermore, by analyzing and clustering the diversity of production systems and assessing their level of integration, this Ph.D. Thesis facilitates knowledge-based decision-making, the design and implementation of targeted and adapted

emission mitigation measures, as well as the promotion of positive economic and social synergies.

Regarding GHG and N emissions, the implementation of adapted strategies allows their mitigation while avoiding possible negative interactions. The obtained results highlight the strong influence of climatic conditions, structural characteristics, and management practices on N and GHG emissions associated with enteric fermentation, fields, and manure management. This allows for future emission reductions while revealing the sector's potential for better integration of circularity practices. In addition, context-specific measures are facilitated by identifying the magnitude and emission sources of DPS. In terms of emission mitigation, reducing the amount of crude protein in the purchased fraction of the diet is an effective strategy to mitigate both GHG and N emissions. Additionally, implementing an anaerobic digestion plant reduced GHG emissions in all assessed DPS but increased N losses only in the intensive Mediterranean DPS. The impact of increased productivity through larger use of concentrates on N losses and GHG emissions varied depending on the farming systems examined. In this sense, the Central European semi-extensive system showed a higher potential for GHG reduction, while the Atlantic semi-extensive system accounted for better results when lowering the N losses. Similarly, shallow slurry injection effectively decreased N losses at the field level, although it increased GHG emissions in the Mediterranean DPS. Substituting urea with ammonium nitrate had different effects on GHG and N emission intensity, with greater potential for mitigation in the Atlantic semi-extensive system. Lastly, rigid slurry covers effectively reduced N losses during storage with minimal impact on the GHG emissions. Furthermore, this Doctoral Thesis shows how the cumulative application of mitigation measures leads to positive synergies in reducing the overall emissions of the farm.

This Ph.D. Thesis presents significant advances in facilitating sustainability decision-making and enabling the implementation of tailored emission mitigation measures in key European DPS. This is done by better understanding the available methodologies and the effect of emission mitigation strategies while considering the diversity of existing production systems. In this way, the implementation of context-specific strategies is favoured, minimizing negative interactions and promoting positive synergies in each particular context.

## Resumen

Los sistemas de producción de vacuno de leche (SPL) forman parte de la columna vertebral del sector agrario europeo. Sin embargo, durante las últimas décadas, múltiples retos han puesto en riesgo su sostenibilidad medioambiental, económica y social. En este sentido, reducir su impacto, asegurar su rentabilidad económica y salvaguardar su contribución a la sociedad, son aspectos clave que deben ser abordados tanto por la comunidad científica, así como por la acción política. No obstante, la falta de conceptos, herramientas y enfoques adecuados, se presenta como un factor limitante a la hora de garantizar la sostenibilidad integrada de los SPL. Para ello, esta Tesis Doctoral aborda algunos de los principales retos del sector en materia de sostenibilidad mediante el desarrollo de conceptos, metodologías y estrategias adaptadas a las necesidades particulares de un amplio abanico de SPL en Europa. A lo largo de cuatro capítulos interconectados, se facilita una toma de decisiones mejor y más adaptada basada en el conocimiento científico. Las investigaciones se centran en la evaluación de las herramientas de análisis de la sostenibilidad, el análisis de la diversidad de sistemas de producción existentes, así como en la mitigación adaptada de las emisiones de gases de efecto invernadero (GEI) y pérdidas de nitrógeno (N) a escala de granja.

En lo que se refiere a la evaluación de herramientas destinadas a la determinación de la sostenibilidad integrada de los SPL a escala de granja, esta Tesis Doctoral presenta un marco cuantitativo que permite un análisis exhaustivo de las mismas. Los resultados obtenidos muestran como los modelos analizados incorporan el 40% del total de los indicadores contemplados. Así mismo, se constata como las herramientas evaluadas presentan un mayor número de indicadores asociados con el pilar medioambiental que con el pilar económico y social. En adición, este trabajo facilita la identificación de vías para el desarrollo futuro de los modelos, permitiendo una más completa y detallada evaluación de la sostenibilidad. Por todo ello, este marco demuestra ser un método eficaz que permite a los usuarios potenciales tomar decisiones basadas en el conocimiento a la hora de elegir las herramientas que mejor se adapten a sus necesidades específicas.

Los resultados obtenidos en materia de análisis de la diversidad de SPL permiten la identificación, descripción y agrupación de las regiones europeas de acuerdo con diferentes tipologías de sistemas productivos. Además, esta Tesis Doctoral evalúa las interacciones existentes entre los sistemas de producción de leche y cultivos forrajeros a lo largo de Europa. Las 16 tipologías representativas identificadas, combinan las características estructurales, productivas, socioeconómicas y medioambientales de los SPL con la distribución de cultivos

forrajeros más relevantes para la producción láctea en 251 regiones NUTS2. Junto con estas tipologías, el análisis de los diferentes grados de especialización regional para la producción láctea, permite identificar futuras estrategias específicas para la promoción de sistemas mixtos (ganadería y cultivos) mediante prácticas de producción integradas a escala regional europea. En adición, al analizar y agrupar la diversidad de sistemas productivos y evaluar su nivel de integración, esta Tesis Doctoral facilita la toma de decisiones basada en el conocimiento, el diseño y la aplicación de medidas de mitigación de emisiones específicas y adaptadas, así como la promoción de sinergias económicas y sociales positivas.

En cuanto a las emisiones de GEI y N, la aplicación de estrategias adaptadas permite la mitigación de las mismas al mismo tiempo que se evitan posibles interacciones negativas. Los resultados obtenidos ponen de manifiesto la gran influencia de las condiciones climáticas, las características estructurales y las prácticas de manejo sobre las emisiones de N y GEI asociadas a la fermentación entérica, los cultivos, así como a toda la cadena de gestión del estiércol. Esto permite la reducción futura de las emisiones media al mismo tiempo que se revela el potencial del sector para una mejor integración de prácticas circulares. En adición, al identificar la magnitud y fuentes de emisión de los SPL, se facilita la aplicación de medidas específicas a cada contexto. En términos de mitigación de las emisiones, la reducción de la proteína bruta en la fracción comprada de la dieta es una estrategia eficaz a la hora de mitigar tanto las emisiones de GEI como las pérdidas de N. Además, la implantación de una planta de digestión anaerobia es efectiva a la hora de reducir la intensidad de GEI en todos los SPL evaluados, aumentando únicamente las pérdidas de N en el sistema mediterráneo intensivo. El impacto del incremento de la productividad a través de un mayor uso piensos sobre las pérdidas de N y las emisiones de GEI es variable entre los sistemas examinados. A este respecto, el sistema semi-extensivo centroeuropeo muestra un mayor potencial de reducción de GEI, mientras que el semi-extensivo atlántico obtiene mejores resultados en la reducción de las pérdidas de N. Del mismo modo, el uso de la inyección de purines reduce las pérdidas de N en campo, incrementando las emisiones de GEI en el sistema mediterráneo. La sustitución de urea por nitrato amónico tiene diferentes efectos sobre los GEI y la intensidad de N, observándose un mayor potencial de mitigación en el sistema semi-extensivo atlántico. Por último, las cubiertas rígidas de purines mitigan eficazmente las pérdidas de N durante el almacenamiento, con un impacto mínimo en las emisiones totales de GEI. Así mismo, a lo largo de esta Tesis Doctoral se demuestra como la aplicación cumulativa de medidas de mitigación, deriva en sinergias positivas a la hora de reducir las emisiones globales de la explotación.



Esta Tesis Doctoral presenta avances significativos a la hora de facilitar la toma de decisiones en materia de sostenibilidad y permite la aplicación adaptada de medidas de mitigación de las emisiones adaptadas en los SPL europeos. Esto se lleva a cabo a través de una mejor comprensión de las metodologías y los efectos de las estrategias de mitigación de emisiones, teniendo en cuenta la diversidad de sistemas productivos existentes. De este modo, se favorece la aplicación de estrategias específicas, minimizando las interacciones negativas y promoviendo las sinergias positivas en cada contexto.

## Resum

Els sistemes de producció de boví de llet (SPL) formen part de la columna vertebral del sector agrari europeu. Tanmateix, durant les últimes dècades, múltiples reptes n'han posat en risc la sostenibilitat mediambiental, econòmica i social. En aquest sentit, reduir-ne l'impacte, assegurar la rendibilitat econòmica i salvaguardar la contribució a la societat són aspectes clau que han de ser abordats tant per la comunitat científica, com també per l'acció política. No obstant això, la falta de conceptes, instruments i enfocaments adequats, es presenta com un factor limitant a l'hora de garantir la sostenibilitat integrada (medi ambient, economia i societat) dels SPL. Per això, aquesta tesi doctoral aborda alguns dels principals reptes del sector en termes de sostenibilitat mitjançant el desenvolupament de conceptes, metodologies i estratègies adaptades a les necessitats particulars d'un ampli ventall de SPL a Europa. Al llarg de quatre capítols interconnectats, es facilita la presa de decisions basades en el coneixement científic sobre la sostenibilitat integrada del sector. Les investigacions se centren en l'avaluació de les eines per a la seua quantificació, l'anàlisi de la diversitat de sistemes de producció existents, així com en la promoció de la circularitat i la mitigació adaptada de les emissions de gasos d'efecte d'hivernacle (GEH) i pèrdues de nitrogen (N) a escala de granja.

Pel que fa a l'avaluació d'instruments destinats a la determinació de la sostenibilitat integrada dels SPL a escala de granja, aquesta tesi doctoral presenta un marc quantitatiu que en permet una anàlisi exhaustiva. Els resultats obtinguts mostren com els models analitzats incorporen el 40% del total dels indicadors previstos. Així mateix, es constata com les eines avaluades presenten un major nombre d'indicadors associats amb el pilar mediambiental que amb el pilar econòmic i social. A més, aquest treball facilita la identificació de vies per al desenvolupament futur dels models i facilita una avaluació de la sostenibilitat més completa i detallada. Per tot això, aquest marc demostra ser un mètode eficaç que permet als usuaris potencials prendre decisions basades en el coneixement a l'hora de triar les eines que millor s'adapten a les seues necessitats específiques.

Els resultats obtinguts en matèria d'anàlisi de la diversitat de SPL permeten la identificació, descripció i agrupació de les regions europees d'acord amb diferents tipologies de sistemes productius. A més, aquesta tesi doctoral avalua les interaccions existents entre els sistemes de producció de llet i conreus farratgers al llarg d'Europa. Les 16 tipologies representatives identificades combinen les característiques estructurals, productives, socioeconòmiques i mediambientals dels SPL amb la distribució de conreus farratgers més rellevants per a la producció làctia en 251 regions NUTS2. Juntament amb aquestes tipologies, l'anàlisi dels

diferents graus d'especialització regional per a la producció làctia permet identificar futures estratègies específiques per a la promoció de sistemes mixtos (ramaderia i conreus) mitjançant pràctiques de producció integrades a escala regional. En addició, en analitzar i agrupar la diversitat de sistemes productius i avaluar el seu nivell d'integració, aquesta Tesi Doctoral facilita la presa de decisions basada en el coneixement, el disseny i l'aplicació de mesures de mitigació d'emissions específiques i adaptades, així com la promoció de sinergies econòmiques i socials positives.

Quant a les emissions de GEH i N, l'aplicació d'estratègies adaptades en permet la mitigació alhora que s'eviten possibles interaccions negatives. Els resultats obtinguts palesen la gran influència de les condicions climàtiques, les característiques estructurals i les pràctiques de maneig sobre les emissions de N i GEH associades a la fermentació entèrica, els conreus, així com tota la cadena de gestió del fem. Això permet la reducció futura de les emissions al mateix temps que es revela el potencial del sector per a una millor integració de practiques de circularitat. De més a més, en identificar la magnitud i fonts d'emissió dels SPL, es facilita l'aplicació de mesures específiques a cada context. En aquest sentit, la reducció de la proteïna bruta en la porció comprada de la dieta és una estratègia eficaç per a mitigar tant les emissions de GEH com les de N. A més, la implantació d'una planta de digestió anaeròbia va reduir la intensitat de GEH en totes les SPL avaluades, augmentant únicament les emissions de N en el sistema mediterrani intensiu. L'impacte de l'increment de la productivitat a través d'un major use pinsos sobre les pèrdues de N i les emissions de GEH va variar entre els sistemes d'explotació examinats. Referent a això, el sistema semi-extensiu centreeuropeu va mostrar un major potencial de reducció de GEH, mentre que el semi-extensiu atlàntic va obtindre millors resultats en la reducció de les pèrdues de N. De la mateixa manera, l'ús de la injecció de purins va reduir les emissions de N a nivell de camp, incrementant les emissions de GEH en el sistema mediterrani. La substitució d'urea per nitrat d'amoni va tindre diferents efectes sobre els GEH i la intensitat de N, observant-se un major potencial de mitigació en el sistema semi-extensiu atlàntic. Finalment, les cobertes rígides de purins van reduir eficaçment les pèrdues de N durant l'emmagatzematge amb un impacte mínim en les emissions totals de GEH. Així mateix, al llarg d'aquesta tesi doctoral es demostra com l'aplicació cumulativa de mesures de mitigació deriva en sinergies positives a l'hora de reduir les emissions globals de l'explotació.

Aquesta tesi doctoral presenta avanços significatius a l'hora de facilitar la presa de decisions en matèria de sostenibilitat i permet l'aplicació de mesures de mitigació de les emissions adaptades en els SPL europeus. Això es duu a terme a través d'una millor comprensió de les metodologies

i efectes de les estratègies de mitigació d'emissions, tenint en compte la diversitat de sistemes productius existents. D'aquesta manera, s'afavoreix l'aplicació d'estratègies específiques, que minimitza les interaccions negatives i promou les sinergies positives en cada context.

## Laburpena

Behi-aziendaren esnea ekoizteko sistemak (EESak) Europako nekazaritza-sektorearen bizkarrezurraren zati dira. Hala ere, azken hamarkadetan, erronka anitzek arriskuan jarri dute haien ingurumen-, ekonomia- eta gizarte-jasangarritasuna. Ildo horretan, haien inpaktua murriztea, haien errentagarritasun ekonomikoa ziurtatzea eta gizarteari egiten dioten ekarpena babestea funtsezko alderdiak dira eta bai komunitate zientifikoak bai ekintza politikoak heldu behar diete. Dena den, kontzeptu, tresna eta ikuspegi egokien falta faktore mugatzailea da EESen jasangarritasun integratua (ingurumenari, ekonomiari eta gizarteari dagokienez) bermatzerakoan. Muga horietarako irtenbideak ekartzeko asmoz, doktorego-tesi honek sektoreak jasangarritasunaren aldetik dauzkan erronka nagusietako batzuei heltzen die. Horretarako, Europako EESen sorta zabal baten behar partikularretara egokitutako kontzeptuak, metodologiak eta estrategiak garatu dira. Elkarrekin konektatutako lau kapitulutan, erabakiak hobeto eta modu egokituagoan hartzeko modu bat, ezagutza zientifikoan oinarritua, aurkezten da. Hona hemen ikerketen ardatzak: jasangarritasuna analizatzeko tresnen ebaluazioa, dauden ekoizpen-sistemen dibertsitatearen analisia eta berotegi-efektuko gasen (BEGen) isurien eta nitrogeno-galeren (N galeren) arintze egokitua abeletxe-eskalan.

EESen jasangarritasun integratuak abeletxe-eskalan zehazteko balio duten tresnen ebaluazioari dagokionez, doktorego-tesi honek tresnok sakonki analizatzea ahalbidetzen duen esparru kuantitatibo bat aurkezten du. Lortutako emaitzek erakusten dute analizatutako ereduak azterturiko adierazle guztien % 40 barne hartzen dituztela. Era berean, egiaztatu da ebaluatutako tresnek adierazle gehiago dauzkatela ingurumen-oinarriarekin lotuta ekonomia- eta gizarte-oinarriarekin lotuta baino. Gainera, lan honek ereduak etorkizunean garatzeko bideen identifikazioa errazten du eta, hala, jasangarritasunaren ebaluazio osoagoa eta zehatzagoa egitea errazten du. Hori guztia dela-eta, esparru hau metodo eraginkorra da, erabiltzaile potentzialei ezagutzan oinarritutako erabakiak hartzea ahalbidetzen diena haien behar zehatzetara hobekien egokitzen diren tresnak aukeratzeko.

EESen dibertsitateari buruzko analisietan ateratako emaitzek ahalbidetzen dute Europako eskualdeak ekoizpen-sistema moten arabera identifikatzea, deskribatzea eta taldekatzea. Gainera, doktorego-tesi honek Europan zehar esnea ekoizteko sistemen eta bazka-laboreen artean daude interakzioak ebaluatzen ditu. Identifikatutako 16 tipologia adierazgarriek EESen egitura-ezaugarriak, ezaugarri produktiboak, ezaugarri sozioekonomikoak eta ingurumen-ezaugarriak konbinatzen dituzte Europako 251 eskualdetako esne-ekoizpenerako garrantzitsuenak diren bazka-laboreen banaketarekin. Tipologia horiekin batera, esne-ekoizpenerako eskualde-

espezializazioaren mailen analisiak ahalbidetzen du Europako eskualde-mailan integratutako ekoizpen-praktiken bidez sistema mistoak (abelzaintza eta laboreak konbinatzen dituztenak) sustatzeko etorkizuneko estrategia zehatzak identifikatzea. Horrez gain, ekoizpen-sistemen dibertsitatea analizatu eta taldekatzen duenez eta haien integrazio-maila ebaluatzen duenez, doktorego-tesi honek isuriak arintzearen arloko erabaki egokituak hartzea eta sinergia ekonomiko eta sozialak sustatzea errazten du.

BEGen isuriei eta N isuriei dagokienez, estrategia egokituak aplikatzeak bidea ematen du isuriok arintzeko eta aldi berean sor daitezkeen interakzio negatiboak saihesteko. Lortutako emaitzek agerian jartzen dute baldintza klimatikoek, egiturazko ezaugarriek eta kudeaketa-praktikek eragin handia dutela hartzidura enterikoarekin, laboreekin eta simaurraren kudeaketa-kate guztiarekin lotutako N isurietan eta BEGen isurietan. Horrek etorkizunean arintze-aukerak egokituz isuriak murriztea ahalbidetzen du eta, aldi berean, sektoreak ekoizpen-sistemen zirkulartasuna hobeto integratzeko duen potentziala agerrarazten du. Gainera, EESen neurria eta isuri-iturriak identifikatuta, testuinguru bakoitzerako neurri zehatzak aplikatzea errazten da. Isuriak arintzeari dagokionez, elikaduran proteina gordineko edukia murriztea estrategia eraginkorra da bai BEGen bai N emisioak arintzeko. Bestalde, digestio anaerobioko instalazio bat ezartzeak BEGen intentsitatea murrizten du, Mediterraneoko sistema intentsiboan N galeak soilik handituz. Pentsu-gehirri handiagorekin lotutako produktibitate-gehikuntzak Nren galeretan eta BEGen isurpenetan duen eragina aldakorra da. Horri dagokionez, Europa erdialdeko sistema erdi-estentsiboak BEGk murrizteko potentzial handiagoa erakusten du. Atlantikoko sistema erdi-estentsiboak, berriz, emaitza hobeak lortzen ditu N galerei dagokienez. Era berean, minda-injekzioaren erabilerak landa-eremuko N galerak emisioak murrizten ditu, Mediterraneoko sistenako BEGk areagotuz. Urearen ordeztar amonio nitratoa erabiltzeak, ondorio desberdinak dauzka BEG eta N emisioetan, sistema erdi estentsibo atlantikoan arintze-potentzial handiagoa erakutsiz. Azkenik, mindak biltegitratzeko estalki zurrinak N galerak eraginkortasunez murrizten ditu, efektu txikia erakutsiz BEGen emisioetan. Era berean, doktorego-tesi honetan frogatzen da arintze-neurrien aplikazio metatuak sinergia positiboak dakartzala ustiatetik isuri globalak murrizterakoan.

Doktorego-tesi honek jasangarritasunaren arloan erabakiak hartzea errazteko aurrerapen nabarmenak aurkezten ditu eta Europako EESetan arintze-neurri egokituak aplikatzea ahalbidetzen du. Hori isuriak arintzeko metodologiak eta estrategiak hobeto ulertuz lortzen da, dauden ekoizpen-sistemen dibertsitatea kontuan hartuta. Modu horretan, estrategia zehatzen

aplikazioaren alde egiten da, interakzio negatiboak minimizatzeko eta testuinguru bakoitzean sinergia positiboak sustatzeko.

## **Zusammenfassung**

Milchviehhaltungssysteme (MPS) sind das Rückgrat des europäischen Agrarsektors. In den letzten Jahrzehnten haben jedoch zahlreiche Herausforderungen ihre ökologische, wirtschaftliche und soziale Nachhaltigkeit in Frage gestellt. In dieser Hinsicht sind die Verringerung ihrer Auswirkungen, die Gewährleistung ihrer wirtschaftlichen Rentabilität und die Sicherung ihres Beitrags zur Gesellschaft wichtige Aspekte, die von der wissenschaftlichen Gemeinschaft und der Politik angegangen werden müssen. In diesem Zusammenhang ist der Mangel an geeigneten Konzepten, Instrumenten und Ansätzen immer noch ein limitierender Faktor bei der Untersuchung der integrierten Nachhaltigkeit von MPS. Zu diesem Zweck werden in dieser Dissertation einige der wichtigsten Herausforderungen des Sektors im Hinblick auf die Nachhaltigkeit angegangen, indem Konzepte, Methoden und Strategien entwickelt werden, die an die besonderen Bedürfnisse eines breiten Spektrums von europäischen MPS angepasst sind. In vier miteinander verknüpften Kapiteln wird eine bessere und gezieltere Entscheidungsfindung auf der Grundlage wissenschaftlicher Erkenntnisse ermöglicht. Besonderes Augenmerk wird auf die Bewertung der Instrumente zur Nachhaltigkeitsbewertung, die Analyse und Clusterbildung der Vielfalt bestehender Produktionssysteme und die angepasste Minderung von Treibhausgasemissionen (THG) und Stickstoffverlusten (N) auf der Ebene der landwirtschaftlichen Betriebe gelegt.

Für die Bewertung von Instrumenten zur integrierten Nachhaltigkeitsbewertung wird in dieser Dissertation ein quantitativer Rahmen vorgestellt, der eine umfassende Bewertung von Instrumenten und Modellen für ganze landwirtschaftliche Betriebe ermöglicht. Im Durchschnitt deckten die Modelle 40 % der gesamten bewerteten Indikatoren ab. Die Ergebnisse zeigen, dass die untersuchten Modelle mehr Indikatoren aus dem Umweltbereich enthalten als solche aus dem wirtschaftlichen oder sozialen Bereich. Darüber hinaus erleichtert diese Arbeit die Identifizierung von Wegen für zukünftige Modellentwicklungen, die eine vollständigere und detailliertere Bewertung der Nachhaltigkeit ermöglichen. Somit wird dieser Rahmen als ein effektiver Ansatz vorgestellt, der es potenziellen Nutzern ermöglicht, wissensbasierte Entscheidungen bei der Auswahl der besten Instrumente für ihre Bedürfnisse zu treffen.

Die aus der Analyse der Vielfalt der MPS gewonnenen Ergebnisse ermöglichen die Identifizierung, Beschreibung und Gruppierung der europäischen Regionen nach verschiedenen Typologien von Produktionssystemen. Darüber hinaus werden in dieser Dissertation die Wechselwirkungen zwischen Milch und Futterpflanzen in ganz Europa bewertet. Die 16 ermittelten repräsentativen Typologien kombinieren die strukturellen, produktiven,



sozioökonomischen und ökologischen Merkmale der MPS mit dem Grad der Überschneidung mit den für die Milcherzeugung wichtigsten Futtermitteln in 251 NUTS2-Regionen. Zusammen mit diesen Typologien ermöglicht der unterschiedliche Grad an regionaler Spezialisierung für die Milchproduktion die Identifizierung zukünftiger gezielter Strategien für gemischte Landwirtschaftssysteme (Pflanzenbau-Viehzucht) durch die Einführung integrierter Produktionssysteme in allen europäischen Regionen. Darüber hinaus erleichtert diese Doktorarbeit durch die Analyse und Clusterbildung der Vielfalt der Produktionssysteme und die Bewertung ihres Integrationsgrades eine wissenschaftliche Entscheidungsfindung, die Konzeption und Umsetzung gezielter und angepasster Emissionsminderungsmaßnahmen sowie die Förderung positiver wirtschaftlicher und sozialer Synergien.

Was die Treibhausgas- und Stickstoffemissionen betrifft, so ermöglicht die Umsetzung angepasster Strategien deren Minderung bei gleichzeitiger Vermeidung möglicher negativer Wechselwirkungen. Die Ergebnisse verdeutlichen den starken Einfluss von klimatischen Bedingungen, strukturellen Merkmalen und Bewirtschaftungspraktiken auf die N- und THG-Emissionen im Zusammenhang mit der enterischen Fermentation, den Feldern und der Güllewirtschaft. Dies ermöglicht künftige Emissionsminderungen und zeigt gleichzeitig das Potenzial des Sektors für eine bessere Integration von Kreislaufwirtschaftsverfahren auf. Darüber hinaus werden kontextspezifische Maßnahmen durch die Ermittlung des Ausmaßes und der Emissionsquellen von MPS erleichtert. Was die Emissionsminderung betrifft, so ist die Verringerung der Menge an Rohprotein in der gekauften Fraktion der Nahrung eine wirksame Strategie, um sowohl die Treibhausgas- als auch die Stickstoffemissionen zu verringern. Darüber hinaus verringerte die Implementierung einer anaeroben Vergärungsanlage die THG-Emissionen in allen bewerteten MPS, erhöhte jedoch die Stickstoffverluste nur in der intensiven mediterranen MPS. Die Auswirkungen der Produktivitätssteigerung durch den verstärkten Einsatz von Kraftfutter auf die N- und THG-Emissionen variierten je nach untersuchtem Anbausystem. In diesem Sinne zeigte das mitteleuropäische semi-extensive System ein höheres Potenzial für die Verringerung der Treibhausgasemissionen, während das atlantische semi-extensive System bessere Ergebnisse bei der Verringerung der Stickstoffverluste erzielte. In ähnlicher Weise verringerte die flache Gülleinjektion die N-Verluste auf der Feldebene, obwohl sie die THG-Emissionen in der mediterranen MPS erhöhte. Der Ersatz von Harnstoff durch Ammoniumnitrat hatte unterschiedliche Auswirkungen auf die Intensität der THG- und N-Emissionen, wobei im atlantischen semi-extensiven System ein größeres Minderungspotenzial festgestellt wurde. Schließlich haben starre Gülleabdeckungen die N-Verluste während der Lagerung bei minimalen Auswirkungen auf die THG-Emissionen wirksam reduziert. Insgesamt zeigt diese Dissertation,

wie die kumulative Anwendung von Minderungsmaßnahmen zu positiven Synergien bei der Reduzierung der Gesamtemissionen des Betriebs führt.

Diese Dissertation stellt einen bedeutenden Fortschritt bei der Erleichterung der Entscheidungsfindung im Bereich der Nachhaltigkeit dar und ermöglicht die Umsetzung maßgeschneiderter Emissionsminderungsmaßnahmen in den wichtigsten europäischen MPS. Dies geschieht durch ein besseres Verständnis der verfügbaren Methoden und der Wirkung von Emissionsminderungsstrategien unter Berücksichtigung der Vielfalt der bestehenden Produktionssysteme. Auf diese Weise wird die Umsetzung kontextspezifischer Strategien begünstigt, wodurch negative Wechselwirkungen minimiert und positive Synergien in jedem einzelnen Kontext gefördert werden.

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## Glossary of terms

**AD:** Anaerobic digestion

**AN:** Ammonium nitrate

**AWU:** Annual working unit

**C:** Carbon

**CAN:** Calcium ammonium nitrate

**CAP:** Common agricultural policy

**CH<sub>4</sub>:** Methane

**CO<sub>2</sub>:** Carbon dioxide

**DPS:** Dairy cattle production system

**EF:** Emission factor

**€:** Euro

**ES:** Ecosystem services

**FADN:** Farm accountancy data network

**FAMD:** Factor analysis for mixed data

**FSS:** Farm structure survey

**GHG:** Greenhouse gas

**IIR:** Informative inventory report

**IPCC:** Intergovernmental Panel on Climate Change

**K:** Potassium

**LU:** Livestock units

**N:** Nitrogen

**N<sub>2</sub>O:** Nitrous oxide

**NH<sub>3</sub>:** Ammonia

**NIR:** National inventory report

**NO<sub>3</sub><sup>-</sup>:** Nitrates

**NO<sub>x</sub>:** Nitrogen oxides

**NUTS:** Nomenclature of territorial units for statistics

**P:** Phosphorus

**PCA:** Principal component analysis

**SO:** Standard output

**UAA:** Utilized agricultural area

# **Chapter 1: General introduction**

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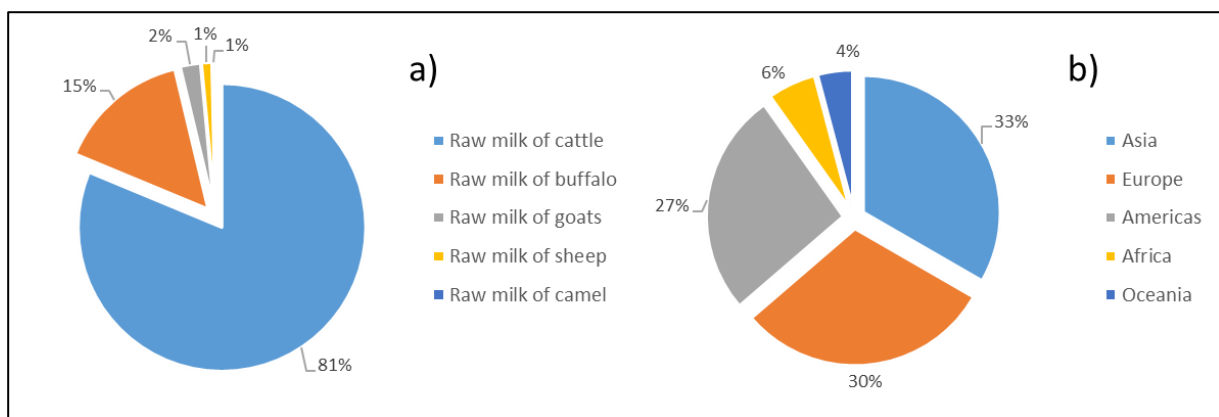
# 1. Dairy cattle production systems (DPS) at the global and European scale

## 1.1. General considerations about DPS

Milk production represents one of the key pillars of world agriculture. According to the Food and Agriculture Organization of the United Nations (FAO), world milk production accounted for 0.9 Gigatonnes (Gt) in 2021, standing as one of the major contributors to the global food and nutrient supply (FAO 2022a). As shown in Figure 1.a, among the different milk typologies (i.e., sheep, goat, buffalo, and camel), cow milk is the most produced and consumed milk by humans due to its availability and large production capacity worldwide (Faye and Konuspayeva 2012; Roy et al. 2020).

Cow milk represents one of the most relevant livestock commodities, As more than 80% of the global population consumes dairy products regularly (FAO and GDP 2019). However, as the world's population increases, the demand and consumption of dairy products are also expected to rise. According to recent statistics, the consumption of dairy products per capita (i.e., milk and its derivatives) is projected to increase by 1.37% globally in the next decade (OECD and FAO 2022). This increase in product demand and the limited availability of raw materials and inputs, are presented as a source of challenges for the sector (FAO 2009). Therefore, ensuring the economic, social, and environmental sustainability of dairy cattle production systems (DPS) is key to maintaining sufficient production levels for adequate food provision at the global and regional scale.

**Figure 1:** Graphical representation of the production of different types of milk by animal category (a) and cattle milk production by global regions (b) for 2021. Source: FAO 2023.

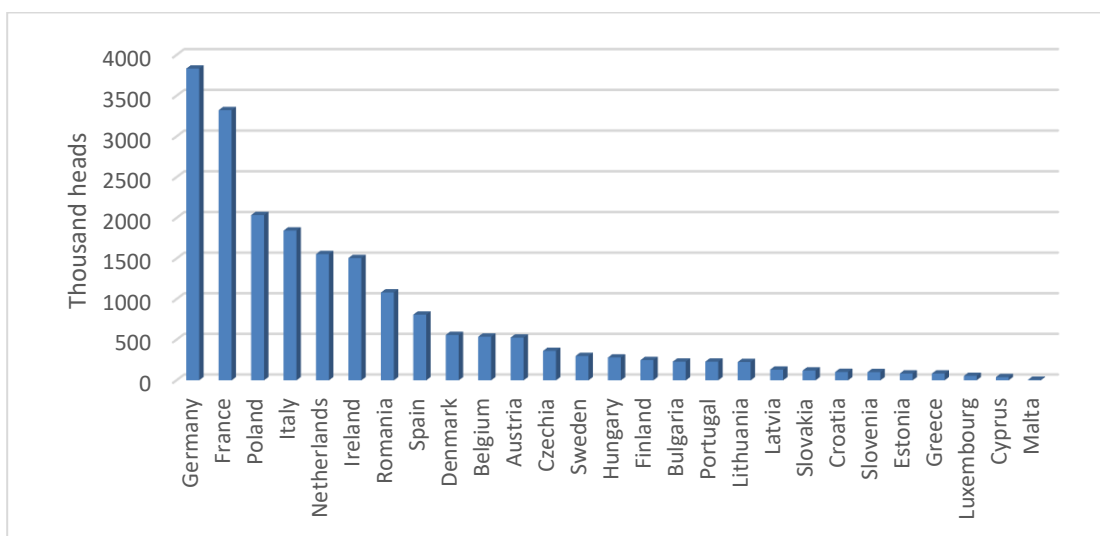


At the European level, cattle milk production reached 0.15 Gt in 2021, making Europe the world's second largest producer by region in terms of total output (30%) only surpassed by Asia (33%) (Figure 1.b) (FAO 2023). Likewise, historically, DPS have been one of the most relevant sectors

of European agriculture, playing a vital role in the development of the region (Van Arendonk and Liinamo 2003). Dairy production represents more than 12% of the EU's agricultural output, ranking as the second most relevant agricultural sector in economic terms (European Parliament 2018). Furthermore, together with beef cattle production, dairy cows in Europe represent the largest livestock type by animal numbers (followed by pig and poultry) with a great diversity of representations and productive contexts throughout the continent (Neumann et al. 2009; Peyraud and Macleod 2020). These differences in production, land use, emissions, or crop-livestock integration levels, are largely determined by each region's socioeconomic and environmental particularities, thus shaping the wide diversity DPS across the EU.

As for today, the distribution of dairy cows throughout the European Union of the 27<sup>1</sup> (EU-27) is heterogeneous. According to official statistics, the EU-27 had a dairy population of 20.2 million heads in 2021 (European Commission 2023). As represented in Figure 2, animal distribution across countries is uneven. Germany has the largest dairy cow population, with 3800 thousand heads (19%), followed by France and Poland (16 and 10%).

**Figure 2:** Dairy cow population (thousands heads) in the EU-27 countries for 2021. Source: European Commission 2023



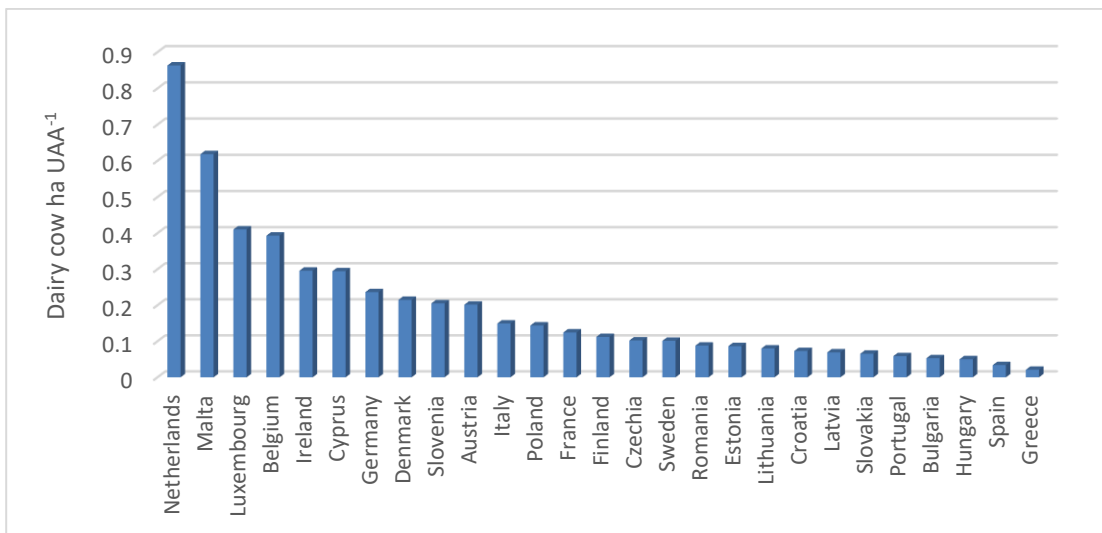
After the removal of the milk production quota in April 2015 (European Commission 2018), cow milk production in the EU-27 has been constant at around 0.15 Gt per year during the last decade, reaching its maximum production levels in 2020 with 0.16 Gt (European Commission 2023). In this sense, productivity among EU-27 countries was 7682 kg of milk per dairy cow per year in 2021. However, the current statistics show heterogeneous values in milk production across

<sup>1</sup> Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.

different regions. While the central and Northern European countries accounted for higher milk yields, Eastern regions of the EU-27 have significantly lower productions. In this sense, Denmark has the highest productivity of the EU-27 with 10097 kg of milk per dairy cow per year. In comparison, Romania and Bulgaria present the lowest productivity, with 3362 and 3628 kg of milk per dairy cow per year, respectively.

Although the number of dairy farms has substantially decreased over the last decades, their size has notably increased, resulting in larger farms with a higher level of specialization (Bas-Defosse et al. 2019). This change in the production systems has been spreading throughout the continent at the expense of small-family-owned farms (Clay et al. 2020; Reinsch et al. 2021). In this context, and as a major descriptor of farm intensification, the animal stocking rate by hectare of total Utilized Agricultural Area (UAA) was heterogeneous across the EU-27 countries for the year 2021. As shown in Figure 3, the highest values were found in the Netherlands and Malta (0.86 and 0.61 dairy cows per ha of UAA), while Spain and Greece had the lowest values (0.03 and 0.02 dairy cows per ha of UAA).

**Figure 3:** Stocking rate of dairy cows per hectare (ha) of total Utilized Agricultural Area (UAA) in the EU-27 countries for 2020. Source: European Commission 2023



Among the variety of existing DPS, "specialized dairy" production is defined as the one in which milk sales account for more than two-thirds of the farm's total standard output (SO) (Unay-Gailhard and Bojnec 2019). According to the data available in Farm Accountancy Data Network (FADN), in 2022 these production systems in the EU-27 averaged an economic size of 136000 euros (€) of SO per farm (European Commission 2022). Denmark presented, on average, the largest farms in terms of economic size (861000€), followed by Slovakia and the Czech Republic,

with 789000 and 564000€ of SO, respectively. On the contrary, Romania had the smallest farms regarding their economic size, with 13000€ of SO.

In addition to supplying society with highly valuable agricultural commodities, DPS are presented as a fundamental pillar in the European socioeconomic development by representing an essential source of employment along the whole production chain. In this context, the dairy industry contributes with more than 1 million direct and indirect jobs across European regions (European Dairy Association 2021). Expressed in total Annual Working Units (AWU), dairy specialist farms in the EU-27 accounted on average for 1.88 AWU in the year 2021. This value was significantly higher in Slovakia and the Czech Republic (22.09 and 12.25 AWU, respectively) than in Romania (1.40 AWU). The jobs derived from DPS are closely linked to rural areas, becoming one of the main drivers of their economic development (Segerkvist et al. 2020). Furthermore, in a context of an increasing abandonment of rural areas, DPS prevents the emigration of the rural population and promotes the local economy (Peyraud and Macleod 2020). This ensures the sustainability of less developed areas through an economic activity deeply rooted in the territory.

## **1.2. Main regulatory framework affecting DPS**

While the diversity of DPS is determined by the climate, topography, soil, and socioeconomic characteristics of each particular region, the current regulatory framework is crucial when shaping the dairy sector across the continent (Bórawski et al. 2020). In this context, DPS in the EU-27 meet the highest quality standards and are at the international forefront of pollution prevention and socioeconomic sustainability thanks to a strong body of legislation.

Numerous national and international policies aim to regulate milk production in a way that ensures its economic, social, and environmental sustainability. Regulations at the European level, such as the Industrial Emissions Directive, the Directive on National Emission Ceilings, the Nitrate Directive, the Water Framework Directive, and the Habitats Directive, are clear examples of the legislation that has to be followed in dairy production activities across the region (European Commission 1991, 1992, 2000, 2010, 2016). Furthermore, this region has been at the forefront of international efforts to fight climate change, being a key actor when brokering crucial transnational agreements. In this context, National climate protection laws aimed to meet the Paris Agreement goals set targets for emission reduction. In compliance with the Kyoto Protocol (UNFCCC 2008) and as part of the European Green Deal, the EU has clear emission reduction

commitments for 2050 that require concrete measures to achieve these targets (European Commission 2019).

Moreover, the limits to global warming agreed during the last decades require mechanisms that allow for proper emission accounting (Leahy et al. 2020). To this end, high-quality, transparent, and accurate reporting metrologies are needed (Amon et al. 2021). In the context of the United Nations Framework Convention on Climate Change (UNFCCC), European and other countries report greenhouse gas (GHG) emissions related to the agricultural sector (including DPS) through National Emissions Inventories Reports (NIR) (UNFCCC 2022). Furthermore, through the Gothenburg Protocol, ammonia (NH<sub>3</sub>) emissions are communicated via the Informative Inventory Reports (IIR) (UNECE 1999).

Concerning policies aimed at maintaining the economic sustainability of the sector, since 1962 the Common Agricultural Policy (CAP) has directly supported prices to secure incomes from European dairy farmers (Jongeneel et al. 2011). In this sense, during the period 2008-2011 the CAP allocated 3.500 million € to the dairy cattle sector. However, farmers and policymakers have criticized the effect of this policy when promoting sustainability in DPS. Furthermore, with the abolition of the milk quota in 2015, new strategies and support systems based on the adaptability of the DPS to the new sustainability challenges are required (Bórawski et al. 2020; Jongeneel and Gonzalez-Martinez 2022). In this context, current European agricultural policies are aligned with the Farm-to-Fork strategy and advocate for the implementation of sustainability principles along the whole production chain bringing climate and environmental objectives to the forefront of political action (European Commission 2020, 2021). Nevertheless, there is a reluctance to adopt them as they could potentially endanger the sector's production capacity leading to price increases (Wesseler 2022).

## **2. The role and impacts of DPS**

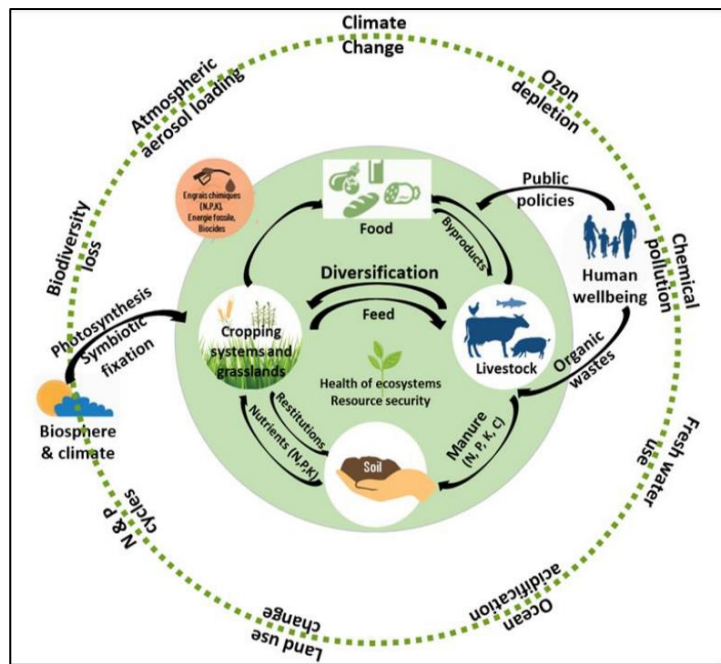
### **2.1. Contribution of DPS to the overall sustainability**

DPS are vital in achieving more environmentally friendly, healthy, and fair food systems while ensuring economic viability and social responsibility (Animal Task Force 2021; Ridoutt et al. 2021). Stressing the role of DPS and adopting holistic approaches is crucial to evaluate their impacts and accurately improve the sector's sustainability (FAO 2014). Therefore, a better understanding of the multifunctionality of DPS is necessary to address the sector's main challenges through adapted and specific policies and measures.

As social awareness regarding climate change increases, there is a need to highlight the importance of the livestock sector in the sustainability framework (Leroy et al. 2022b). As shown in Figure 4, besides playing one of the most relevant roles in the European first-sector's economy, DPS are a relevant actor in the development of the societies by making more efficient use of resources (Animal Task Force 2021). Compared to other livestock systems, ruminants (i.e., DPS) can feed on nutrients from marginal lands unsuitable for cultivating edible protein products for humans (Röös et al. 2017; Poore and Nemecek 2018). Recent studies have pointed out the link between livestock systems and the bio-economy principles as they transform forages and agricultural residues into food and services (Ertl et al. 2015; FAO 2021; Paltaki et al. 2021). Regarding feed-use efficiency at the global scale, ruminants need 5.9kg of human-edible feed to produce 1 kg of protein. In comparison, this value is significantly higher in the case of monogastric animals with 15.8kg (Mottet et al. 2017). These results show the greater efficiency of these systems compared to other livestock production systems.

Although some narratives seem to downplay the role of DPS in global nutrition, dairy products are essential in many countries (i.e., the global South) (Prosekov and Ivanova 2018). However, the current elevated consumption in the Western world requires a detailed analysis of their roles and impacts for the sake of the environment while ensuring the necessary product supply. When comparing dairy products to plant-based options, recent studies demonstrated how cow milk is especially relevant for vulnerable groups such as the young and the elderly as they constitute an excellent source of macro and micronutrients (FAO 2022b; Singh-Povel et al. 2022). Furthermore, as a paradigm of balanced nutrient intake, dairy products are part of the Mediterranean diet (Hinrichs 2004). This highlights the need for a moderate inclusion of these products in our nutritional strategies to maintain an optimal health status (Bach-Faig et al. 2011). In this context, there is a need to ensure a correct supply of quality, safe and healthy products while responding to the economic, social, and environmental challenges derived from their production (Animal Task Force 2019).

**Figure 4:** Role of livestock in the sustainability circle. Source: Animal Task Force 2021.



Several studies have pointed out the negative effect of intensive agricultural practices on soil quality degradation due to overexploitation and the loss of nutrients (i.e., nitrogen (N), phosphorus (P), and potassium (K)) (Jones et al. 2012). This is causing a reduction in crop yields, seriously threatening global food security (Kopittke et al. 2019). In this scenario, humans apply large amounts of fertilizers to agricultural systems to keep crop yields stable (Mason et al. 2022). This application dramatically contributes to widening the carbon (C), N, and P cycles and reducing organic matter and soil fertility. However, in the current context of scarcity of mineral fertilizers and high social costs associated with their usage, the revalorization of agricultural and livestock residues as sources of organic nutrients is becoming increasingly needed (Wei et al. 2020). Here, the role of DPS is vital since they provide the agricultural sector with organic amendments (i.e., manure and slurry), which could replace the use of mineral fertilizers in adequate doses. Moreover, the controlled application of manure derived from DPS activity contributes significantly to the reduction of inputs and to better connecting crop-livestock systems (Billen et al. 2021).

Besides providing food and inputs (i.e., organic fertilizers), DPS supply society with multiple intangible benefits and services. These are known as Ecosystem Services (ES) and are defined as resources or processes of natural ecosystems (and their species) that benefit or sustain the human population (Daily 1997). Although this term was adopted several years ago, it is still relevant and paves the way for the valorization of the sector in terms of its environmental contribution. These ES can be divided into 4 main categories: provisioning, regulatory, supporting, and cultural

services. Even if their relevance depends to a greater or lesser extent on the production system we are assessing, their social and environmental importance is undeniable. In this context, specific DPS typologies like pasture-based systems, play a substantial role (D'Ottavio et al. 2018). Certain practices associated with different grazing options are associated with higher carbon sequestration values, higher soil fertility, and increased pasture productivity, among other benefits (Cao et al. 2018; Díaz de Otálora et al. 2021). Moreover, DPS are vital in optimizing multiple ecological processes and promoting traditions. This is reflected in efforts to conserve local breeds, biodiversity, and habitats (Beal et al. 2022).

## **2.2. The environmental impact of DPS**

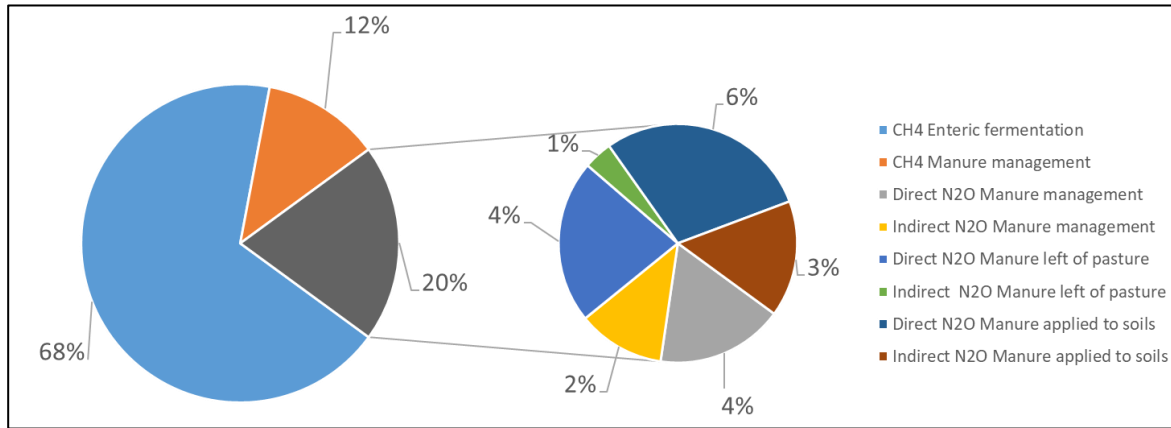
### **2.2.1. Greenhouse gas emissions and nitrogen losses**

Although the role of DPS in Europe's economy, society, and environment has been widely acknowledged, the sector needs to tackle the challenges associated with climate change and negative environmental impacts. Dairy cattle production can imply severe impacts on the environment and ecosystems. Among others, the emission of pollutants to water and the atmosphere (i.e., GHG and N losses) stands out as the main adverse effects of this sector (Centre for European Agricultural Studies 2000). Although these impacts vary greatly depending on the production system and location (Hristov et al. 2013), their accounting and consideration are necessary when considering appropriate measures for their reduction.

Globally, 14.5% of anthropogenic GHG emissions come from the livestock sector (Gerber et al. 2013b). Of these emissions, 20% are directly associated with milk production, representing 2.7% of total anthropogenic-derived ones (Tricarico et al. 2020). Within the agricultural sector of the EU-27, DPS represent a major source of GHG emissions mainly due to the on-farm emission of nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) (UNFCCC 2023). Statistics from international organizations such as FAO, show the magnitude of these emissions and their most prominent sources. In this context, CH<sub>4</sub> emissions for EU-27 countries for the year 2020 (i.e., enteric fermentation and manure management) accounted for 2738 kilotons (kt) of CH<sub>4</sub>, while nitrous oxide (N<sub>2</sub>O) emissions reached a value of 2.57 kt of N<sub>2</sub>O (FAO 2023). As can be seen in Figure 5, manure and enteric CH<sub>4</sub> emissions account for more than three-quarters of the on-farm emissions associated with DPS, followed by N<sub>2</sub>O emissions from fields and manure. Furthermore, other sources of off-farm GHG emissions, such as feed production, also play a relevant role in the balance of DPS emissions (de Vries et al. 2019)



**Figure 5:** On-farm GHG emission sources (percentage (%) of CO<sub>2eq</sub>) for dairy cattle production in EU-27 countries for the year 2020. Source: FAO 2023



Aside from N<sub>2</sub>O, reactive N losses (i.e., run-off and leaching) in the form of NH<sub>3</sub>, nitrates (NO<sub>3</sub><sup>-</sup>), and nitrogen oxides (NO<sub>x</sub>) represent one of the greatest impacts from livestock production as they contribute to the eutrophication and acidification processes (Novak and Fiorelli 2009; Joy et al. 2022; McDowell et al. 2022). As for NH<sub>3</sub>, livestock production is responsible for 64% of total global emissions, with DPS being one of the most significant sources (Hristov et al. 2011; Sanchis et al. 2019). Furthermore, roughly 50% of the N excreted was retained on the farm, while the remaining is considered nutrient loss (Oenema et al. 2007).

Although DPS are becoming more and more efficient (FAO and GDP 2019), the current GHG and N emissions significantly contribute to environmental deterioration and represent a risk to human health (Grout et al. 2020). Both the global warming effect associated with CH<sub>4</sub> and N<sub>2</sub>O emissions and the eutrophication/acidification processes derived from N losses (i.e., NH<sub>3</sub>) are significant drawbacks of dairy production (Place and Mitloehner 2010; Grossi et al. 2019). Even though the magnitude of these adverse effects varies depending on the production system, their reduction is imperative. As a first step, evaluating these impacts in detail could allow for the successful design, implementation, and monitoring of strategies for their reduction.

### 2.2.2. Emission modelling and quantification

Given the diversity of GHG and N emission sources from DPS, tailor-made strategies for their quantification are needed. To this end, tools and approaches considering aspects such as diet composition, herd management, manure management, and fertilization are necessary to obtain a detailed overview of the farm's general environmental performance. Assessing all these aspects in an integrated and systemic manner allow for a comprehensive analysis of the most relevant C

and N flows in the farms, enabling a deeper understanding of the drivers that affect GHG and N emissions at the system level (Olesen et al. 2006).

Quantifying emissions from livestock systems is challenging, as it requires a thorough assessment of the various relationships between the farm's biotic and abiotic factors (Ouatahar et al. 2021). In this sense, a wide range of approaches and tools has been developed in the last decades to help stakeholders estimate and report emissions. The Intergovernmental Panel on Climate Change (IPCC) presents three calculation methods with different levels of complexity and accuracy for quantifying emissions. Tier 1 is the most basic method using default emission factors (EF). Tiers 2 and 3 are more precise calculation methods requiring more data for their application (Calvo et al. 2019). These EFs are mainly derived from literature reviews or experiments with limited scope for different pollutants and emission sources and present different levels of complexity and accuracy when using national-specific data (Tier 2) or model simulations (Peter et al. 2016; Ahmed et al. 2020). However, using EF alone fails to determine farm-level emissions of particular scenarios.

While EF are particularly suitable for developing emission inventories or identifying emission trends at different scales, whole-farm models integrate the loops and interactions of different management practices in a systemic manner on DPS (Crosson et al. 2011). Process-based whole-farm models make it possible to determine emissions at a lower cost, in terms of time and money, while simultaneously enabling the analysis of the effect of specific production strategies from a system perspective (Rotz 2018). By integrating EF and mechanistic approaches, whole-farm models allow for a better understanding of DPS by simulating their response to changes and identifying the most appropriate practices for each context. In this sense, the implementation of effective mitigation options would benefit from integrating system approaches as internal feedback and loops between various farm components could be captured (Del Prado et al. 2013).

### **3. Challenges of the DPS**

Given the challenges threatening the dairy cattle sector across Europe, integrated, context-specific, and adapted approaches are necessary to enhance the positive role and reduce the negative impacts of DPS. However, to date, their application is limited by the lack of knowledge about three aspects:

1. The adequacy of the available tools to assess integrated sustainability.
2. The diversity of DPS across European regions.

3. The uncertain effect and interactions of different mitigation options to reduce GHG and N emissions on wide range of DPS.

This requires the adoption of specific solutions to ensure the sector's future economic, social, and environmental sustainability.

### **3.1. Adequacy of the available tools to assess integrated sustainability on DPS**

Over the last years, the design and implementation of integrated practices fostering the transition of the livestock sector towards sustainability have moved to the forefront of public opinion and scientific production (Valencia et al. 2019; Lerma et al. 2022). Achieving this integrated sustainability involves considering all aspects and dimensions related to DPS while keeping, as much as possible, a balance between them. This would favour the identification of the most relevant trade-offs and synergies between the social, economic, and environmental aspects affecting DPS (Clay et al. 2020).

European DPS continue to face many challenges across the three pillars of sustainability (i.e., social, economic, and environmental). The farm-level strategies proposed to address these sustainability challenges are highly diverse, and tools to assess their effectiveness and impacts are scarce. In this context, using an integrated approach when determining the sustainability of DPS is key to address the challenges affecting a wide range of farming enterprises (Van Calker et al. 2001; Passel et al. 2006). However, adopting an integrated approach to evaluate sustainability is still troublesome (Feil et al. 2020). To date, several studies have focused on analyzing one of the dimensions of sustainability in a disaggregated manner (Acosta-Alba et al. 2012; Borawski et al. 2020; Brennan et al. 2020). This results in an uneven consideration of the multiple aspects of sustainability, leading to an incomplete or partial analysis of the nuances affecting sustainability. Therefore, to better evaluate the overall sustainability performance of DPS, attributes related to the three pillars of sustainability must be jointly considered. Although several approaches currently consider these three dimensions (Del Prado et al. 2011; Rotz et al. 2022), there are significant constraints in determining which of these tools are most appropriate in each context. This is presented as a critical challenge, as it often restricts the implementation of proper measures to enhance the sector's sustainability due to an unspecific assessment of the farm's main challenges.

While the diversity of whole-farm models has been previously assessed from the modelling perspective (Rotz 2018), there is an evident knowledge gap regarding their quantitative assessment. In this context, it is vital to develop, test and implement tailor-made methods and

approaches to identify the most appropriate assessment framework according to the user's needs to facilitate decision-making in the integrated sustainability assessment process. These methodologies should indicate the strengths and weaknesses of each sustainability assessment tool by considering the most relevant attributes of the three pillars of sustainability. However, to date, there is a lack of such evaluation methodologies, thus limiting the adequate integrated assessment of the sustainability of the DPS. Therefore, developing quantitative evaluation frameworks (based on commonly acknowledged criteria) will allow for a comprehensive assessment of different attributes of whole-farm models dealing with integrated sustainability. Hence, a better understanding of the available tools could be facilitated, thus enabling an adequate selection of the best-suited tool.

### **3.2. Diversity of DPS across regions in Europe**

European regions are highly diverse and complex, consisting of extensive, semi-intensive, and intensive production systems using multiple resources to produce a wide range of dairy products and other services. The diversity and complexity of livestock systems challenge the sustainability concepts, strategies, and policies to be applied (Rivera-Ferre et al. 2016). Hence, actions to better assess this diversity could allow overcoming this limitation due to a better assessment of the complex reality.

The transition towards production intensification has increased the differences between DPS throughout Europe (Poczta et al. 2020). Therefore, approaches that consider context-specific conditions are required to adequately address regional particularities within the three pillars of sustainability. Furthermore, adapted methodological frameworks need to be developed to assist dairy farmers in creating robust and resilient farms able to address the upcoming economic and environmental challenges (EIP-AGRI 2018). Many production patterns, climatic conditions, structural characteristics, and socioeconomic attributes shape European DPS. Moreover, their spatial distribution and management practices play a fundamental role in sector diversity, as they can lead to heterogeneous levels of specialization across the territory (Bijttebier et al. 2017; Reinsch et al. 2021). In order to adequately address the particular needs of each production context, the deployment of the abovementioned adapted approaches is needed. To this end, identifying representative DPS typologies at a regional scale could allow for a better understanding of the abovementioned diversity by analyzing the characteristics of the production systems in an integrated manner. Thus, knowledge-based decisions that address this challenge from a holistic perspective could be taken as a necessary step before implementing effective policies toward sustainability.

To date, several studies have attempted to identify, describe, and compare different typologies across the dairy farming sector in Europe. While these studies have focused on assessing single aspects or limited geographical contexts for DPS (Gonzalez-Mejia et al. 2018; Poczta et al. 2020), further research is needed to integrate economic, social, and environmental attributes on a broader scale. Due to the lack of integrated perspective, current approaches are insufficient or have a limited scope for application when designing, implementing, and monitoring different sustainability concepts, strategies, and policies. This existing knowledge gap on DPS typologies at the regional scale hinders the implementation of sustainability measures such as emissions mitigation options or circularity practices. Therefore, adopting a holistic perspective when identifying representative DPS typologies requires considering European farms' socioeconomic, structural, and environmental aspects. As opposed to the "one-fits-all" solutions, adapting measures through representative typologies at the regional scale will facilitate the implementation of context-specific measures through knowledge-based decisions based on each productive scenario's particular needs and characteristics.

### **3.3. Effect and interactions of different mitigation options to reduce GHG and N emissions**

Even if DPS represent one of the primary sources of GHG and N emissions, there is considerable scope for their reduction if adequate measures are applied (FAO 2017). Far from being a limitation, the diversity DPS allows for addressing emission mitigation from different approaches. In addition, due to the rising need to take concrete actions towards controlling and modulating these emissions, solid premises in favour of more environmentally friendly DPS must be settled (Pérez-Domínguez et al. 2021; Leroy et al. 2022a).

In this context, robust tools and approaches are needed to analyze the interactions between dairy production typologies, farm characteristics, and emission sources. However, the current scientific knowledge fails in this process, as there is still a lack of knowledge about the relationship between different GHG and N emissions and the particularities of DPS across Europe. This hinders the implementation of adapted measures and increases uncertainty about their effectiveness in reducing emissions and promoting sustainability. In this context, a detailed analysis of the level of influence of the different intrinsic characteristics of each DPS on emissions would address this challenge, contributing to informed decision-making.

DPS are highly heterogeneous, and so are their GHG emissions and N losses. The analysis of dairy farms from a systemic perspective makes it possible to identify the sources and quantify the magnitude of emissions, allowing the adaptability of mitigation options. At the farm scale,

three significant sources of emissions have been identified: i) the animal, ii) manure management, and iii) the fields (FAO 2010). Different production systems (i.e., intensive, extensive, semi-extensive), diets, manure management, or fertilization strategies shape these emissions and their sources. Therefore, addressing them with an integrated and adapted approach could reduce emissions while avoiding negative trade-offs.

### **3.3.1. Options at the animal level**

Dairy animals are considered one of the most relevant sources of emissions from DPS (Koenen et al. 2013). Enteric CH<sub>4</sub> derived from the microbial fermentation of carbohydrates in the rumen of the cows, is the main contributor to the overall GHG budget from DPS (Gerber et al. 2013a). In addition, N losses (i.e., NH<sub>3</sub> and N<sub>2</sub>O) associated with excreta, mainly derived from an excess of protein in the diet, constitute one of the most relevant sources of environmental impact from animal origin (Dijkstra et al. 2013). In this sense, multiple strategies have been developed during the last decades to reduce these emissions while keeping productivity (de Haas et al. 2021). Several studies have emphasized the positive effect of higher digestibility (i.e., replacing low-quality forages) or lower crude protein content in the diet on reducing GHG emissions and N losses (Dijkstra et al. 2018; Olijhoek et al. 2018). Likewise, improved animal genetics, as well as the use of different additives (i.e., 3-Nitrooxypropanol), have been described as effective mitigation measures of GHG emissions at the animal level (Knapp et al. 2014; González-Recio et al. 2020).

### **3.3.2. Options at the manure management and fertilization level**

Manure handling and use represent a focus for action when reducing the environmental impact of DPS (Petersen 2018). As mentioned by previous authors, manure during housing, storage, and application, play a fundamental role in the overall emissions from DPS as significant sources of CH<sub>4</sub>, N<sub>2</sub>O, and NH<sub>3</sub> (Hou et al. 2015; Wattiaux et al. 2019). Therefore, mitigating these emissions along the entire manure management chain is paramount for reducing the environmental impact of DPS. In this sense, several authors have analyzed different strategies targeting manure management that lead to emissions reduction at the farm scale. Additives (i.e., urease inhibitors), the solid-liquid separation of the manure, and anaerobic digestion have been described as effective emission mitigation strategies (Aguirre-Villegas et al. 2019; Bobrowski et al. 2021). As for the slurry-manure storage facilities, even if the different technologies present varying emission reduction potentials, using covers is a widely accepted technology to reduce emissions from manure storage (Kupper et al. 2020; European Court of Auditors 2021). Finally, as for the application of manure in the fields, several studies described the positive effect of appropriate

application timing and methods (i.e., shallow injection) have in the reduction of the volatilization of N in the form of NH<sub>3</sub> (Maris et al. 2021).

In addition to organic fertilizers, DPS make intensive use of mineral fertilizers such as urea, ammonium nitrate (AN), or calcium ammonium nitrate (CAN). Their use contributes significantly to NH<sub>3</sub> and N<sub>2</sub>O emissions from fields (Sommer et al. 2001; Chai et al. 2019), increasing the overall budget emission from DPS. In order to reduce these emissions, several studies have addressed the development, implementation, and evaluation of fertilizers with lower emissions (i.e., nitrification inhibitors), allowing for substantial emission reductions at the field level (Rodhe et al. 2006; Forrestal et al. 2019; Lasisi et al. 2020).

### **3.4. Adapted application of mitigation options**

Identifying adequate practices to reduce emissions is necessary to tackle the environmental impact of DPS (Burney et al. 2010). However, mitigation options are diverse in economic, social, and environmental terms, and their performance in reducing emissions is highly variable depending on the context (Eugène et al. 2021). In this sense, previous authors have highlighted the need to consider the particularities of agricultural systems for the implementation of mitigation measures at the European scale (Pérez-Domínguez and Fellmann 2015). Far from universal solutions, emissions mitigation requires specific approaches considering each farm's particularities.

Although the effect of mitigation options on single gases and emission sources has been widely described in the literature, a deeper understanding of the possible pollutant swapping that may result from their application is required. In this line, previous authors have highlighted how the same mitigation strategies lead to different results depending on the characteristics of each production system (Dutreuil et al. 2014; Beukes et al. 2019). These conflicting results largely condition the adoption of these measures and limit their positive effect. In order to reduce this uncertainty, promote positive synergies and reduce negative trade-offs, the adaptation of mitigation measures to the particular characteristics of the DPS is crucial. This requires the application of integrated approaches that analyze all components of dairy farms in a combined manner (i.e., manure management chain) prior to the identification of the best suitable option to mitigate GHG and N emissions.

Furthermore, when applying emission mitigation measures, their effect on other aspects of sustainability needs to be contemplated (i.e., economic and social). Enhancing the environmental sustainability of DPS by reducing GHG and N emissions may require significant investments in

new techniques or infrastructures, thus affecting the economic sustainability of DPS. In addition, a mitigation strategy that improves the environmental sustainability of DPS could affect the quality of life of the farmers affecting social pillar of sustainability. Even if the interactions between sustainability pillars across DPS are numerous and complex, their consideration could support the adaptation and success of future integrated practices.

In all, promoting the sustainability of DPS requires a better knowledge of the available tools, a better analysis of the sector's diversity, and the adaptation of the emission mitigation options and strategies to region-specific conditions. In this context, facilitating knowledge-based decisions is vital to foster the resilience and sustainability of DPS. Therefore, considering different contexts and system components will ensure optimal performance without jeopardizing the achievement of the sustainability goals of the sector across Europe.

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## **Chapter 2: Aims and Ph.D. Thesis structure**

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This Ph.D. Thesis aims to address the sustainability of key European dairy cattle production systems (DPS) by evaluating existing sustainability tools, assessing the production systems, and tailoring mitigation measures for greenhouse gas (GHG) and nitrogen (N) emissions. To this end, a holistic approach is applied, considering all sustainability pillars (economic, social, and environmental), the diversity of DPS, and their emissions. In this sense, the main specific objectives of this Doctoral Thesis are the following:

1. **Objective 1:** To develop, implement, and test a methodological framework based on quantitative indicators to evaluate the suitability of whole-farm models to assess the integrated sustainability of DPS.
2. **Objective 2:** To address the diversity of DPS at the regional scale in Europe by identifying, describing, and clustering representative typologies based on the integration between dairy and fodder crop production systems.
3. **Objective 3:** To assess the level of influence that different management practices and structural features have on the sources of GHG and N emissions in key DPS across Europe.
4. **Objective 4:** To analyze the individual and combined effect of the tailored application of GHG and N emission mitigation options and their trade-offs on the most relevant emission sources of key DPS across Europe.

To answer the research questions posed by the four objectives described above, this Ph.D. Thesis has led to four chapters.

The **third chapter** of this Ph.D. Thesis addresses the diversity of existing tools for assessing integrated sustainability at the farm scale by developing a quantitative assessment framework that allows evaluating the degree of inclusion of attributes of each sustainability pillar by the tool subject to study (*Objective 1*). This evaluation framework has been conceived to facilitate tool selection based on objective criteria and according to the specific needs of each user.

To better understand the diversity of DPS across Europe and their interaction with the most relevant fodder crops, the **fourth chapter** of this Ph.D. Thesis applies a multivariate statistical approach for determining representative typologies at the regional scale (*Objective 2*). To this end, indicators from international databases are collated to allow for a detailed analysis of the different production contexts, thus enabling the analysis of integrated crop-livestock systems.

The diversity of tools and production contexts analyzed in the **third and fourth chapters** of this Ph.D. Thesis lays a solid foundation for improving DPS's sustainability by applying tailored

measures to reduce GHG and N emissions. In this context, the **fifth** and **sixth chapters** use a context-specific approach that allows for identifying and analyzing the individual and combined effects of emission mitigation practices. The **fifth chapter** identifies and describes the degree of influence that different management practices and structural characteristics have on the sources of GHG and N emissions from key DPS across Europe, allowing for the analysis of the main emission drivers and the potential application of circularity practices (*Objective 3*). The **sixth chapter** focuses on analyzing the effect of different mitigation measures on the most relevant gases and emission sources of the DPS, allowing for the implementation of measures based on identifying possible negative trade-offs and positive synergies (*Objective 4*).

Finally, the results obtained from the **third, fourth, fifth and sixth chapters** are jointly discussed in the **seventh chapter**. Here we indicate the contribution of each of the studies carried out, their limitations, and the avenues open for future research. Moreover, the general conclusions of the Ph.D. Thesis are presented in the **eight chapter**.

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# Chapter 3: Evaluating three pillar sustainability modelling approaches for dairy cattle production systems

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## **Abstract**

Milk production in Europe is facing major challenges to ensure its economic, environmental, and social sustainability. It is essential that holistic concepts are developed to ensure the future sustainability of the sector and to assist farmers and stakeholders in making knowledge-based decisions. In this study, integrated sustainability assessment by means of whole-farm modelling is presented as a valuable approach for identifying factors and mechanisms that could be used to improve the three pillars (3P) of sustainability in the context of an increasing awareness of economic profitability, social well-being, and environmental impacts of dairy production systems (DPS). This work aims (i) to create an evaluation framework that enables quantitative analysis of the level of integration of 3P sustainability indicators in whole-farm models and (ii) to test this method. Therefore, an evaluation framework consisting of 35 indicators distributed across the 3P of sustainability was used to evaluate three whole-farm models. Overall, the models integrated at least 40% of the proposed indicators. Different results were obtained for each sustainability pillar by each evaluated model. Higher scores were obtained for the environmental pillar, followed by the economic and the social pillars. In conclusion, this evaluation framework was found to be an effective tool that allows potential users to choose among whole-farm models depending on their needs. Pathways for further model development that may be used to integrate the 3P sustainability assessment of DPS in a more complete and detailed way were identified.

**Key words:** sustainability, dairy farm, integrated, whole-farm models, and evaluation.

## 1. Introduction

The global demand for livestock products is expected to increase by up to 70% by 2050 (Opio et al. 2013). In this context, dairy production systems (DPS) constitute an essential backbone of European agriculture, producing high-quality protein products that are key for our diets by means of fibrous feed resources that cannot be directly utilized by humans or converted to human food by monogastric animals (van der Ploeg et al. 2019; Wodajo et al. 2020). Products derived from this sector (mainly milk and its derivatives) represent the largest animal product category in the European Union (EU) (Bórawski et al. 2019). The high level of production linked to the increasing demand for these products by EU citizens (Westhoek et al. 2011) highlights the importance of this sector from economic, social, and environmental points of view. In addition, the livestock sector, and in particular the DPS, is a potential contributor within the framework of the circular economy (Ghisellini et al. 2014; Lybæk and Kjær 2019). Livestock are resource recyclers by nature, but the conditions under which livestock can enhance circularity and play a decisive role in the development of more sustainable farming systems need to be defined. The circular bio-economy requires a switch from maximizing single products and single process efficiency to having a comprehensive focus on the use of resources within the whole food system and the integration of production systems in territories and food chains (European Commission 2018; Animal Task Force 2019).

In previous decades, multiple initiatives aimed at expanding existing knowledge on livestock system sustainability assessments have arisen on different geographical scales. The Global Research Alliance (GRA) aims to reduce the emission intensity of livestock production systems by optimizing food production (Clough et al. 2020; Pérez-Barbería 2020). In addition, through the guide- lines for Sustainability Assessment of Food and Agricultural Systems (SAFA), the Food and Agriculture Organization of the United Nations (FAO) has developed a framework that could serve as a holistic tool for the assessment of sustainability in food and agriculture value chains (FAO 2016; Cammarata et al. 2021). At the European scale, the Modelling European Agriculture with Climate Change and Food Security initiative (MACSUR) highlights the existence of different sustainability assessment models in the context of livestock and agriculture, enhancing the integration between them (Ma et al. 2014; Köchy et al. 2015). Created under the framework of the EU Joint Programming Initiative for Agriculture, Climate Change, and Food Security, MACSUR also aims to analyze the contributions of these models in terms of coping with climate change in the EU by, for example, using integrated modelling in the animal production sector.

There is an urgent demand for identification and quantitative assessment of win–win (synergy) or second-best (trade-off) solutions by improving knowledge of the systemic relationships in such complex systems (Joint Programming Initiative on Agriculture 2020). The ability to account for interactions among livestock systems, the environment, and on-farm management decisions makes integrated modelling an appropriate approach when assessing sustainability in DPS (Kipling et al. 2016). Application of this integrated approach has been described as indispensable for understanding the different interacting subsystems inside a farm (Schils et al. 2007a). When integrating aspects using the 3P of sustainability, it is necessary to identify, describe, and analyze the different external factors, both positive and negative, associated with livestock activity (Mehrabi et al. 2020). For instance, the generation of employment throughout the production chain and the production of high-quality protein products for consumption in less developed areas are considered positive effects of livestock that are related to all three pillars of sustainability (Adesogan et al. 2020). In contrast, the negative external factors associated with sustainability derived from livestock activities are mainly due to their contributions to greenhouse gas (GHG) and nitrogen (N) emissions and the use of natural resources (Herrero et al. 2016; Ibidhi and Calsamiglia 2020). In the process of identification, analysis, and evaluation of these sustainability aspects, farm-level assessment tools are highly valuable for researchers, practitioners, and farmers (Arulnathan et al. 2020; Coteur et al. 2020). In this context, whole-farm models are presented as appropriate tools to encompass individual farm processes through a complete and integrated dairy system assessment (Beukes et al. 2008). These tools allow the quantification of socioeconomic and biophysical farm processes in order to achieve concrete management objectives according to specific farm situations (Eichler et al. 2018).

Whole-farm integrated sustainability modelling requires clear identification of both the inputs of the system and the outputs derived from the livestock activity itself. An ideal whole-farm model should be able to integrate attributes of the three pillars of sustainability as well as represent existing synergies and trade-offs between them (Schils et al. 2007b). It is essential that holistic concepts are developed to ensure the sustainable economic, environmental, and social development of DPS. By integrating economic, social, and environmental sustainability indicators into the assessment, synergies, and trade-offs of economic costs, social and environmental impacts can be quantified, leading the sector on a more socioeconomically and environmentally sustainable path. To date, a wide variety of whole-farm sustainability assessment tools with different objectives have been developed (Robertson et al. 2012). However, limited attention has been paid to the evaluation processes associated with these tools, resulting in a lack of guidance when deciding which tool should be used (De Olde et al. 2016).

The sustainability of agricultural production has moved to the forefront of public concern and the political agenda (Balaine et al. 2020; Alem 2021). The use of an integrated approach when evaluating the sustainability of DPS has been described as a very effective method to satisfy the economic needs of farmers, the well-being of society, and the environmental conditions in which livestock activity takes place (Passel et al. 2006; Thomassen et al. 2009). In this context, the use of a common framework for evaluating the suitability of models to assess 3P sustainability in DPS allows clear boundaries on what a balanced model should analyze to be established, enabling informed selection of which model to use.

For these reasons, the aim of this paper is to establish and test a framework that can be used to evaluate the suitability of models to assess 3P sustainability in DPS. This method allows the different aspects of tools related to the 3P of sustainability to be investigated and the level of completeness with which the proposed indicators are integrated to be assessed, facilitating the selection of the tool that best fits the needs of the users.

## 2. Materials and Methods

### 2.1. Evaluation framework

An in-depth analysis was carried out with the objective of identifying the number and typologies of the sustainability indicators used in the existing literature. For this purpose, a literature search was carried out using the Scopus database. Papers including the terms “sustainability indicators” and “livestock farming” in the title, abstract, or keywords were considered. The search was carried out in December 2020.

As a primary output, 21 references were identified, from 3 papers (Table 1) for which the following criteria applied: (i) only articles published in English-language peer-reviewed journals were selected; (ii) the papers should include indicators of the three pillars of sustainability (economic, social, and environmental); and (iii) the context of application of the indicators included in these papers is focused on the dairy industry (both dairy cattle and sheep). Papers whose scope was not directly related to the sustainability of DPS as a whole (e.g., sustainability of cropping systems only) were excluded from this analysis.

**Table 1:** Final output of the literature research for the indicator compilation

Reference	Journal	Publication year	DOI
(Galioto et al. 2017)	Sustainability	2017	10.3390/su9091615
(Lebacqz et al. 2013)	Agronomy for Sustainable Development	2013	10.1007/s13593-012-0121-x
(Ripoll-Bosch et al. 2012)	Agricultural Systems	2011	10.1016/j.agsy.2011.10.003

A list of 35 indicators was derived from the three selected papers (Table 2): 11 within the economic pillar, 7 within the social pillar, and 17 within the environmental pillar. The economic pillar indicators included aspects associated with profitability, autonomy, farm diversification, and durability. Social sustainability was represented by indicators related to education, working conditions, quality of life, and ecosystem services. Environmental sustainability incorporated indicators related to farm management, greenhouse gases and reactive nitrogen emissions, and soil/water quality.

**Table 2:** List of the indicators for the 3P of sustainability used for the evaluation framework

Sustainability pillar	Attribute	Indicator
Economic (n=11)	Profitability	Net farm income
		Land productivity
		Animal productivity
	Autonomy	Feed efficiency
		Economic self-sufficiency
		Feed self-sufficiency
	Farm diversification	Food production
		Economic diversification
		Non-food earnings
		Added value products
	Durability	Succession and transmissibility
Social (n=7)	Working conditions	Work balance
		Labour efficiency
	Quality of life	Job satisfaction and personal development
		Animal welfare
	Ecosystem services	Environmental conservation
	Maintenance of landscape	
		Ecosystems regulation
Environmental (n=17)	Farm management	Land use
		Erosion
		Energy use
		Water use
		Pesticide use
	Reactive nitrogen (N <sub>r</sub> )	NH <sub>3</sub> emissions
		NO <sub>x</sub> emissions
		CH <sub>4</sub> enteric fermentation
	Greenhouse gases	CH <sub>4</sub> manure
		N <sub>2</sub> O soils
		N <sub>2</sub> O manure
		CO <sub>2</sub> fossil fuels
	Soil/water quality	Nutrient cycling
		Acidification processes
		Eutrophication processes
		Water balance
		Soil quality

## 2.2. Model Selection and Description

Among the wide variety of farm-level sustainability assessment tools available, whole-farm models represent one of the most frequently used typologies to quantify the sustainability of farms. In order to identify whole-farm models that can be used to test the proposed evaluation framework, a literature search was carried out using the Scopus database. We searched for the presence of the terms “dairy farm”, “model\*”, and “sustainability” in the title, abstract, or keywords. The literature search took place in December 2020.

As a primary output, 105 references were identified, from which 3 different models (Table 3) containing the following criteria were selected: (i) published in English-language peer-reviewed journals; (ii) specialized models dealing with DPS; (iii) clearly defined boundaries (whole-farm) in the models; and (iv) integration of all 3P of sustainability (environmental, economic, and social).

**Table 3:** Final output of the literature research for identification of the models to be tested

Model	Full name	References	Origin	Data requirements	Main outputs
SIMSDAIRY	Sustainable and Integrated Management Systems for Dairy Production	(Del Prado and Scholefield 2008; Del Prado et al. 2011)	United Kingdom and Spain	Herd characteristics, diet composition, farm management, biophysical characteristics	Nutrient flows, GHG emissions, herd performance, socioeconomic sustainability and animal welfare and ES
GAMEDE	Global Activity Model for Evaluation Sustainability of Dairy Enterprises	(Vayssières et al. 2009a, b)	France	Herd characteristics, diet composition, farm management and biophysical characteristics	Nitrogen dynamics, forage and herd performance and work requirements
WLGP	Weighted Linear Goal Programming model for dairy farms	(van Calker 2005; van Calker et al. 2008)	Netherlands	Herd characteristics, diet composition, farm management and socio-economic performance	Nutrient flows, GHG emission, economic performance, working conditions, animal welfare and ES

### 2.2.1. SIMSDAIRY

The Sustainable and Integrated Management Systems for Dairy Production, or SIMSDAIRY, is a modelling framework that integrates the fundamental aspects of the management of a whole farm within an interrelated system (Del Prado et al. 2011). SIMSDAIRY is able to analyze the different interactions among farm management, genetics, climatic conditions, and environmental characteristics on a monthly basis and check the effects of these on GHG emissions, economic



factors, and nutrient flows, as well as other sustainability attributes such as biodiversity, animal welfare, milk quality, and soil quality.

Originally developed for the framework of the United Kingdom (UK), SIMS<sub>DAIRY</sub> has proven its suitability for modelling the integrated sustainability of different production systems (organic, conventional, etc.). The semi-mechanistic approach used by SIMS<sub>DAIRY</sub> allows for the simulation of environmental pollution losses with an assessment of financial and socioeconomic sustainability. In addition, SIMS<sub>DAIRY</sub> is able to simulate the trade-offs and synergies between the different components of the model, thus optimizing the management practices to achieve more sustainable livestock activity.

### **2.2.2. GAMEDE**

The Global Activity Model for Evaluating the Sustainability of Dairy Enterprises, or GAMEDE, is a modelling approach that aims to represent dynamic livestock systems (Vayssières et al. 2009a). This whole-farm scale model aims to assess the consequences of a farmer's daily management decisions on whole-farm sustainability on an annual basis (intra-annual variability is also described). GAMEDE is a hybrid model that incorporates mutually dependent variables, thus representing the state of the livestock system at all times. Developed in a temperate climate context, GAMEDE is presented as a model that is potentially applicable to any other geo-climatic context.

Composed of more than 26,000 variables, GAMEDE was designed as a stock-flow model aimed at representing the operation and management of a farm and its effects on technical-economic viability, respect for the environment, and social livability. By quantifying the existing interactions in such a complex system, the user can better understand the processes regulating the nitrogen dynamics within the farm and the factors determining farmers' decisions and practices (Vayssières et al. 2009b).

### **2.2.3. WLGP**

The Weighted Goal Linear Programming-model (WGLP) for dairy farms is a sustainability assessment tool that integrates the economic, social, and environmental sustainability aspects of a dairy farm (van Calster et al. 2008). This whole-farm model analyzes the interrelations between the biophysical, economic, and social processes (internal and external) of a dairy farm. Designed for Dutch milk production systems, the model aims to analyze the sustainability of DPS from the

perspective of individual aspects related to each sustainability pillar or from an integrated perspective, taking into account the preferences of potential stakeholders.

This model integrates a multi-attribute function that allows the sustainability of the different production systems analyzed to be maximized. In this way, the model is not only able to identify the impact of different management practices, but it can also identify existing synergies and trade-offs. The indicators for each of the pillars were selected by potential users (stakeholders) according to their importance, feasibility, and sensitivity. This facilitates the integration of these indicators in an ad hoc general analysis for each production system.

### 2.3. Model Evaluation

The evaluation of the tools was carried out following a threefold approach. First, each model was evaluated by identifying the indicators included in the evaluation framework. The presence or absence of an indicator in the model was indicated in a binary manner (using 0 for absence and 1 for presence).

In a second step, the percentage of indicators included in each model for each sustainability pillar from all established indicators for the related pillar was calculated using the following Equation (1):

$$\%I_{pillar} = \left( \frac{N_{pillar}}{T_{pillar}} \times 100 \right) \quad (1)$$

where  $\%I$  is the percentage of indicators included in the model for each pillar (economic=*econ*, social=*soc*, and environmental=*env*),  $N$  is the number of indicators considered by the model for each pillar, and  $T$  is the total number of indicators for each pillar. All scores are given as a % over the total number of indicators assessed for each case.

In a third step, the Integrated Sustainability Score (*IScore*) was calculated. This score was used to evaluate the global percentage with which the models integrated the sustainability indicators proposed by the evaluation framework taking into account the average values of indicators included for each pillar. For this purpose, the following Equation (2) was used:

$$IS_{score} = \left[ \frac{\left( \left( \frac{N_{econ}}{T_{econ}} \times 100 \right) + \left( \frac{N_{soc}}{T_{soc}} \times 100 \right) + \left( \frac{N_{env}}{T_{env}} \times 100 \right) \right)}{3} \right] \quad (2)$$

where *IScore* represents the Integrated Sustainability Score.

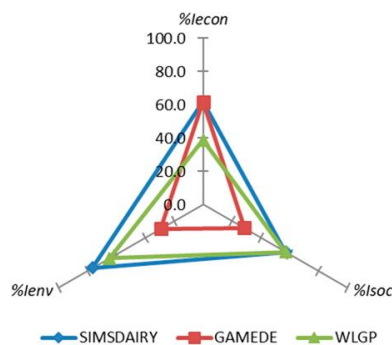
### 3. Results and Discussion

#### 3.1. Economic Sustainability

The economic sustainability of a farm can be defined as its long-term viability (Zorn et al. 2018). By integrating farm profitability, autonomy, diversification capacity, and durability, models can represent economic sustainability. The SIMS<sub>DAIRY</sub> and GAMEDE models integrated equal percentages of economic indicators (62%), while a lower number of indicators was observed in the WLGP model (39%) (Figure 1). Although aspects related to farm profitability, such as “net farm income”, “land productivity”, “animal efficiency”, and “feed efficiency”, are assessed by all three models, a lack of detail has been identified when integrating farm diversification into the modelling schemes. In this context, future model developments should incorporate different approaches to quantify “nonfood earnings” and “economic diversification” as descriptors of farm autonomy.

In a scenario where multi-functionality plays an increasingly important role, capturing the economic diversification of a farm can help to represent the different externalities derived from farming activities (Ohe 2011; Yoshida et al. 2019). Identifying, analyzing, and integrating economic returns associated with livestock activity but not directly related to it, such as educational/pedagogical activities, agritourism, and other “nonfood earnings”, has a positive effect on the level of detail with which the economic sustainability is assessed. Furthermore, consideration of the milk quality and enhanced nutritional composition of the products (e.g., unsaturated fatty acids) would potentially increase the accuracy with which the models assess “product diversification” and “added-value products” (Del Prado et al. 2011; Alvarez et al. 2018; Secco et al. 2020). Similarly, the use of by-products in the composition of animal feed, energy generation, or fertilizers significantly contributes to farm autonomy by enhancing the “feed self-sufficiency” and “economic self-sufficiency” levels while fostering the carbon and nutrient circularity of the farm (Burggraaf et al. 2020; Díaz de Otálora et al. 2020; Natalello et al. 2020).

**Figure 1:** Individual scores obtained for each of the pillars of sustainability by the models included in the evaluation



Modelling the durability of a farm based on its capacity for “succession and transmissibility” is a major topic that has been addressed by a large number of papers (Hennessy 2002; Wheeler et al. 2012; Santhanam-Martin et al. 2019). None of the models evaluated incorporate this aspect in their modelling schemes. Due to both the complex assessment process (long-term farm dynamics) and the lack of a consolidated evaluation framework, simplified approaches are needed to capture these aspects (Leonard et al. 2017). In this context, belonging to farm partnerships or cooperatives has been described as an influential factor in facilitating farm succession and transferability (Leonard et al. 2017; Thorsøe et al. 2020). Future model developments should aim to incorporate information on farmers’ partnerships in order to integrate this aspect of economic sustainability.

### **3.2. Social Sustainability**

In the context of an increasing intensification of DPS, the social pillar of sustainability represents a link between dairy farming and its effects on society. In this regard, the SIMS<sub>DAIRY</sub> and WLGP models showed equal levels of inclusion (57% of the indicators) for indicators related to ecosystem services (ES), animal welfare, and working conditions on the farm. However, the GAMEDE model obtained lower inclusion scores for 29% of the indicators proposed (Figure 1), all of them describing working conditions on the farm. “Job satisfaction”, “personal development”, and “work balance” of the farmer are considered fundamental aspects of DPS social sustainability (Costa et al. 2013; Besser and Mann 2015) that are not fully covered by the three models evaluated. In this context, implementation of the latest available technical and technological advancements in terms of milking systems has been described as a powerful driver for increasing the satisfaction and personal development of farmers (Hansen 2015). The presence of an automatic milking system on farms has been pointed out as a way of increasing personal well-being and development, since it reduces the amount of time spent on paperwork related to farm management tasks, promotes contact between farmers, reduces workforce needs, optimizes the worktime of farmers, and improves the social perceptions of farming activity (Steenefeld et al. 2012; Hansen and Stræte 2020).

Higher educational levels were correlated with greater “labor efficiency” in terms of the use of workforce on farms. An increased level of education was shown to have a positive effect on the average and marginal productivity of a farm (Nowak and Kijek 2016). As described in other studies, having a well-established professional development system enables dairy farm workers to improve their professional skills and keeps them in touch with the latest farming techniques (Dillon et al. 2016; McDonald et al. 2016; Chen and Holden 2017). Future model developments could consider the abovementioned proxies for education level and machinery availability as a

way to assess job satisfaction levels, personal development of farmers, work balance, and labor efficiency. Regarding animal welfare, different levels of inclusion were identified for each model. While the SIMS<sub>DAIRY</sub> and WGLP models incorporate this aspect in their modelling schemes, the GAMEDE does not make any reference to it. Both models quantify animal welfare through the use of scores. In the case of the WGLP model, scores are highly dependent on the type of housing present on a farm, as well as the grazing system used (Bartussek 1999). The SIMS<sub>DAIRY</sub> model also bases its score on the existing grazing system but additionally incorporates factors related to the livestock density, animal productivity, and biophysical characteristics of the grazing area (Müller-Lindenlauf et al. 2010).

Ecosystem services (ES) are major contributors to social and human well-being and can be considered key indicators for the adequate representation of DPS social sustainability (Schmidt et al. 2016; Costanza 2020). The models included in this evaluation were found to have heterogeneous results with regard to the incorporation of ecosystem services (ES) in their modelling schemes. Although the GAMEDE model stresses the importance of the effects of management practices on the biophysical processes of these complex agro-ecosystems, it does not make any explicit reference to the ecosystem services derived from DPS activity in its modelling scheme (Vayssières et al. 2009a). By using existing approaches or proxies to identify, incorporate, and assess ES, models should integrate the effects of these aspects into the social pillar of sustainability. This is the case for the SIMS<sub>DAIRY</sub> and WGLP models (van Calker et al. 2008; Del Prado et al. 2011), which include a scoring system for the quantification of environmental conservation, ecosystem regulation, and landscape conservation services. By using indicators related to grazing, the fertilization rate, the seeding and cutting strategy, and soil structure, the model calculates a score that estimates the value of services such as biodiversity, soil quality, and landscape maintenance.

### **3.3. Environmental Sustainability**

The ever-growing intensification of DPS has resulted in an increase in the environmental impacts of the sector (Eshel et al. 2014; Cortez-Arriola et al. 2016). Whole-farm models should be able to integrate the effects that different management practices have on the environmental pillar of sustainability (Clay et al. 2020). In this regard, in both the SIMS<sub>DAIRY</sub> and WGLP models, the highest scores were obtained in the environmental pillar, 77% and 65%, respectively. The GAMEDE model showed a 30% level of inclusion for the proposed indicators (Figure 1). Differences were observed in both the number and types of farm management attributes integrated by the models. The SIMS<sub>DAIRY</sub> and WGLP models integrate aspects related to “land

use”, “erosion”, “energy use”, and “water use”, while the GAMEDE model only incorporates indicators describing “land use” on a farm. As part of “land use”, grazing practices and rotational crops have been described as potential contributors to environmental and social sustainability, given their positive effects on climate change mitigation and their promotion of ES (Teague and Kreuter 2020; Zhang et al. 2021). As part of an interconnected system, applying regenerative grazing practices could positively affect the economic and environmental sustainability of the farms by increasing both topsoil carbon storage and spring grass production (Díaz de Otálora et al. 2021). The different land uses are reflected by the models through the use of different cover typologies. The GAMEDE model identifies three land-use management-related typologies ranging from grazing to cultivation of varieties for silage or even non-harvesting (Vayssières et al. 2009b). In the same way, SIMS<sub>DAIRY</sub> simplifies the usual on-farm forage covers to four: grass grazed by dairy cows, grass grazed by followers, grass cut for silage, and maize cut for silage. Through this simplification, the model integrates the crops necessary to complete animal dietary requirements that are not covered by concentrates. In addition, this model is capable of determining the risk of “erosion” in the field by estimating sediment loss. Furthermore, the use of pesticides has been associated with negative impacts on the environment due to their elevated ecotoxicity potential (Huijbregts et al. 2000). The WGLP model integrates different pesticide typologies depending on the type of crop grown. In this way, the model is able to estimate different associated emissions and impacts (Van Calster et al. 2004).

Although the relationships among the different livestock activities and the emissions related to their energy consumption has been described by other authors (De Haan et al. 2007), it is necessary to incorporate simple methods for estimating energy consumption as a proxy for future calculation of their associated CO<sub>2</sub> emissions. In this regard, the SIMS<sub>DAIRY</sub> model allows different types of fuel and electricity consumption to be linked to different activities within a farm. In this way, and by applying different factors for each farm activity (e.g., milk production, field operations, slurry management, feeding practices, etc.), the model enables estimation of the consequent CO<sub>2</sub> emissions (Todde et al. 2017). Furthermore, while aspects related to the “water balance” are addressed by the models evaluated, “water use” remains one of the most challenging aspects to model within the DPS. Water consumption by dairy farms is largely conditioned by the climatic conditions, evapotranspiration, herd characteristics, and animal performance (Higham et al. 2017; Shine et al. 2018).

GHG emissions, nitrogen losses, and associated processes, such as “eutrophication” and “acidification”, stand out as the major negative consequences of farming activities (Hennessy et al. 2020). Both the SIMS<sub>DAIRY</sub> and WGLP models comprehensively describe these aspects in

their modelling schemes, while GAMEDE only considers nutrient cycling and CO<sub>2</sub> emissions in its modelling scheme. In the context of better integration of these environmental impacts, emissions derived from enteric fermentation, animal excreta, and manure management have been described as the main contributors to the negative consequences of DPS, mainly due to emissions of CH<sub>4</sub>, NH<sub>3</sub>, NO<sub>x</sub>, and N<sub>2</sub>O, both to the atmosphere as well as to soil and water (Dijkstra et al. 2018). In this regard, diet composition has usually been described as a key indicator when modelling these emissions (Kidane et al. 2018). This fact has been widely assessed by other authors, who have pointed out the relationship of GHG emissions and nitrogen losses with the composition of the diet (protein, fiber, fat, dry matter, etc.) as well as the manure management practices (Gerber et al. 2013; Ricci et al. 2013; Petersen 2018; Ouatahar et al. 2021). For the latter, different manure storage and application strategies have been associated with different levels of CH<sub>4</sub>, N<sub>2</sub>O, and NH<sub>3</sub> emissions. The three models evaluated in this study incorporate comprehensive indicators related to manure management, such as manure type, storage systems, and applications rates, in their modelling schemes. Under the scenario of an increase in the amount of waste derived from the activity of DPS, the valorization of these by-products is presented as system-based solution for GHG emission mitigation in the context of the circular bio-economy (Parfitt et al. 2010; Garcia et al. 2019). Models could analyze the role of biogas plants in their modelling schemes by integrating metrics related to the quantity of energy produced, the amount of sub-product used, and the operating costs, contributing significantly to the level of detail with which the model assesses this pillar of sustainability (Garcia et al. 2019).

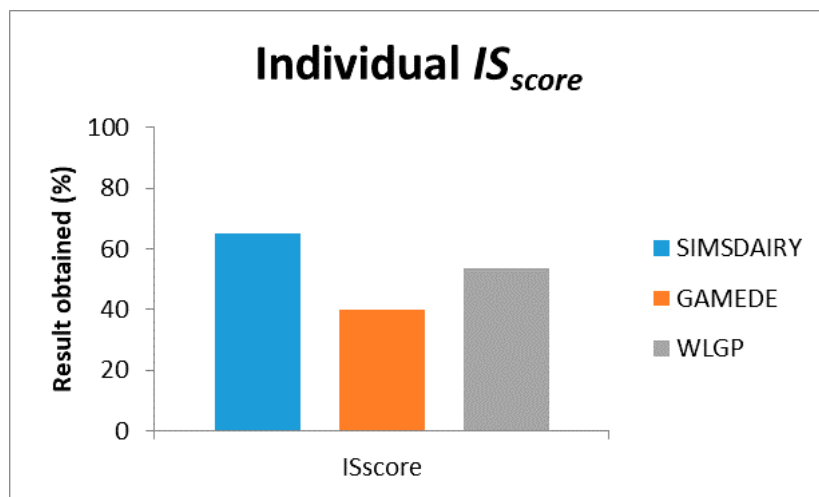
### **3.4. Overall Sustainability**

The calculation of the Integrated Sustainability Score (*ISscore*) for each of the three models showed different results for the tools evaluated. The quantitative analysis of the indicators integrated by each model identified the SIMS<sub>DAIRY</sub> model as the one with the highest level of integration of the sustainability indicators, obtaining an *ISscore* result of 65%. The *ISscore* for the WLGP model was 53%, and the GAMEDE model had the lowest overall value, 40% (Figure 2).

This study focused on the design, application, and testing of a quantitative method for the evaluation of whole-farm models oriented toward the analysis of the integrated sustainability of DPS. Further refinements of the framework should focus on incorporating this two-fold approach in the evaluation process by assessing both the total number of indicators included as well as their type and importance. In this context, many authors have highlighted the need to progress toward sustainability assessment models that encompass both the number of indicators and their roles in

the context in which they are obtained (Scerri and James 2010; Reid and Rout 2020). The variability and vulnerability of the sector highlights the need to incorporate mechanisms that allow the adoption of context-specific solutions (Ruiz Morales et al. 2019). Hence, stakeholder participation processes as part of multi-criteria decision-aid methods are valuable approaches that can be used to seek weighted solutions to the challenges faced by the sector in each context (Martín-Collado et al. 2013; Belanche et al. 2021). These methods set up tailored weights to the different indicators evaluated, facilitating the integration of a qualitative analysis in a transparent, flexible, and feasible way, making it possible to reach specific sustainability solutions in a more efficient manner (Sadok et al. 2009). In this regard, through a joint assessment, models should be able to increase the level of information available to potential users of these tools and, consequently, facilitate the choice of one or more tools, depending on their needs.

**Figure 2:** Individual Integrated Sustainability Scores (*ISscore*) obtained for each model evaluated



#### 4. Conclusions

In conclusion, this whole-farm model evaluation framework is presented as an innovative tool that gives the user a clear overview of the characteristics of each model by describing the degree to which the integrated sustainability of the DPS is assessed. As a consequence, informed decisions can be made by the user when choosing one model over another. Of the whole-farm models evaluated, the SIMS<sub>DAIRY</sub> model was found to be the one that integrates the aspects proposed by the evaluation framework to the greatest extent. Even though indicators of the 3P pillars of sustainability are already included in the three evaluated models, future development of the models should include the identification and integration of the social and economic aspects of DPS sustainability in a more comprehensive manner. In addition, further improvement of the evaluation framework by incorporating a qualitative analysis using focus groups, interviews, and



surveys could be beneficial for conducting holistic assessments of whole-farm integrated sustainability models for DPS.

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## **Chapter 4: 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<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), and ammonia (NH<sub>3</sub>) (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 Rööös 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).

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:** Indicators used to identify and describe the different regional dairy cattle and fodder crop production systems. Emissions for CH<sub>4</sub> from enteric fermentation, CH<sub>4</sub> from manure management and direct N<sub>2</sub>O emissions from manure management were considered. LU livestock units; UAA utilized agricultural area; AWU annual working units; GHG greenhouse gases; CO<sub>2</sub> carbon dioxide; NH<sub>3</sub> ammonia; FSS farm structure survey; NIR national inventory report; IIR informative inventory report.

Name of the indicator	Unit	Description	Sources
<b>Dairy cattle production indicators</b>			
Average animal number per farm	LU farm <sup>-1</sup>	Farm herd size	
Average farm size by total UAA	ha farm <sup>-1</sup>	Farm area	
Average milk yield per cow	kg LU <sup>-1</sup> year <sup>-1</sup>	Animal productivity	
Average workforce per farm	AWU farm <sup>-1</sup>	Number of total workers per farm	
Average share of family workforce per farm	-	Ratio of family workers over the total number of workers per farm	
Average share of arable land over the total UAA per farm	-	Ratio between arable land area and UAA per farm	
Average share of permanent grassland over the total UAA per farm	-	Ratio between permanent grasslands area and UAA per farm	
Average livestock density over total UAA per farm	LU ha <sup>-1</sup>	Intensity of the use of land for dairy production per farm	FSS, NIR and IIR
Average share of owned land over rented land	-	Land ownership per farm	
Average emission intensity of total GHG*	kgCO <sub>2eq</sub> kg <sup>-1</sup>	Intensity of total GHG emissions per kilogram of raw milk	
Average emission intensity of NH <sub>3</sub> from manure management	Kg NH <sub>3</sub> kg <sup>-1</sup>	Intensity of NH <sub>3</sub> emissions from manure management per kilogram of raw milk	
<b>Fodder production indicators</b>			
Ratio of permanent grasslands over the total UAA of the region	-	Share of UAA used for permanent grasslands	
Ratio of temporary grasslands over the total UAA of the region	-	Share of UAA used for temporary grasslands	
Ratio of green maize over the total UAA of the region	-	Share of UAA used for green maize	
Ratio of leguminous crops over the total UAA of the region	-	Share of UAA used for leguminous crops	

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):

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

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<sub>3</sub>) 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<sub>4</sub> emissions from enteric fermentation, ii) CH<sub>4</sub> emissions from manure management, and iii) direct N<sub>2</sub>O 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):

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

Where  $E_{reg}$  is the emission intensity per unit of product for each one of the GHG at a NUTS2 scale (kgCO<sub>2eq</sub> kg milk<sup>-1</sup>),  $GHG_{total}$  are the total national emissions for dairy cattle for each GHG category (kgCO<sub>2eq</sub>),  $POP_{reg}$  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):

$$\sum GHG = E_{CH_4_{ent}} + E_{CH_4_{man}} + E_{N_2O_{man}} \quad (3)$$

Where  $\sum GHG$  is the total GHG emission intensity of milk production (kgCO<sub>2eq</sub> kg<sup>-1</sup>),  $E_{CH_4_{ent}}$  are the CH<sub>4</sub> emissions from enteric fermentation (kgCO<sub>2eq</sub> kg<sup>-1</sup>),  $E_{CH_4_{man}}$  are the CH<sub>4</sub> emissions from manure management (kgCO<sub>2eq</sub> kg<sup>-1</sup>) and  $E_{N_2O_{man}}$  are the direct N<sub>2</sub>O emissions from manure management (kgCO<sub>2eq</sub> kg<sup>-1</sup>). Individual GHG emissions for CH<sub>4</sub> and N<sub>2</sub>O were converted to CO<sub>2eq</sub> using the Global Warming Potential (GWP100) for the year 2021 (Arias et al. 2021). GWP values of 27.2 and 273 were used for the CH<sub>4</sub> and N<sub>2</sub>O respectively.

In order to estimate the intensity of NH<sub>3</sub> 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):

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

Where  $NH_{3total}$  is the regional NH<sub>3</sub> emission intensity per unit of product,  $NH_{3man}$  accounts for the national NH<sub>3</sub> 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<sup>-1</sup>) 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<sub>3</sub> emissions are provided in the Supplementary Material 2.

## **2.2. 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 2022). 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).

### **2.2.1. 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.

### **2.2.2. 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.

### **2.2.3. 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<sub>3</sub> 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.

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<sub>3</sub>. 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 2, 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<sub>3</sub> emission intensity, the number of animals per hectare of UAA, and the share of owned land

**Table 2:** Descriptive statistics (mean and standard deviation) and statistical differences across obtained DPS clusters. Different subscripts indicate statistical significance ( $p < 0.005$ ). \*Indicators not used in the clustering exercise. LU livestock units; UAA utilized agricultural area; AWU annual working units; GHG greenhouse gases; CO<sub>2</sub> carbon dioxide; NH<sub>3</sub> ammonia.

	Units	Cluster 1 (n=116)	Cluster 2 (n=17)	Cluster 3 (n=105)	Cluster 4 (n=13)	Chi <sup>2</sup>	p-value
Average animal number per farm	LU farm <sup>-1</sup>	108.4±56.23 <sup>b</sup>	353.7±134.04 <sup>a</sup>	54.3±38.94 <sup>c</sup>	56.2±55.75 <sup>c</sup>	98.34	<0.001
Average of farm size by total UAA*	ha farm <sup>-1</sup>	86.8±44.50 <sup>b</sup>	287.7±139.93 <sup>a</sup>	45.5±32.63 <sup>c</sup>	12.5±13.73 <sup>d</sup>	108.07	<0.001
Average milk yield per animal	kg LU <sup>-1</sup> year <sup>-1</sup>	7803.9±2253.47 <sup>b</sup>	9371.1±3055.81 <sup>a</sup>	6169.1±1849.87 <sup>c</sup>	3132.5±1111.92 <sup>d</sup>	100.92	<0.001
Average workforce per farm	AWU farm <sup>-1</sup>	2.54±1.042 <sup>b</sup>	8.02±2.594 <sup>a</sup>	1.89±0.444 <sup>c</sup>	1.36±0.762 <sup>d</sup>	90.38	<0.001
Average share of family workforce per farm	-	0.25±0.136 <sup>b</sup>	0.07±0.059 <sup>c</sup>	0.39±0.150 <sup>a</sup>	0.39±0.101 <sup>a</sup>	82.30	<0.001
Average share of arable land over the total UAA per farm	-	0.70±0.162 <sup>a</sup>	0.65±0.131 <sup>ab</sup>	0.40±0.185 <sup>c</sup>	0.51±0.200 <sup>bc</sup>	108.44	<0.001
Average share of permanent grassland over the total UAA per farm*	-	0.30±0.167 <sup>c</sup>	0.35±0.123 <sup>cb</sup>	0.60±0.186 <sup>a</sup>	0.49±0.201 <sup>ab</sup>	103.90	<0.001
Average livestock density over total UAA per farm	LU ha <sup>-1</sup>	1.45±0.808 <sup>b</sup>	1.32±0.400 <sup>b</sup>	1.33±0.559 <sup>b</sup>	5.07±2.205 <sup>a</sup>	33.98	<0.001
Average ratio of owned land over rented land	-	1.14±1.198 <sup>b</sup>	0.50±0.539 <sup>c</sup>	1.78±1.612 <sup>a</sup>	5.07±7.081 <sup>a</sup>	29.41	<0.001
Average emission intensity of total GHG	kgCO <sub>2eq</sub> kg raw milk <sup>-1</sup>	0.58±0.107 <sup>c</sup>	0.50±0.107 <sup>d</sup>	0.72±0.198 <sup>b</sup>	1.45±0.652 <sup>a</sup>	96.89	<0.001
Average emission intensity of NH <sub>3</sub> from manure management*	KgNH <sub>3</sub> kg raw milk <sup>-1</sup>	0.003±0.0011 <sup>c</sup>	0.002±0.0013 <sup>c</sup>	0.003±0.0019 <sup>b</sup>	0.008±0.0062 <sup>a</sup>	32.86	<0.001

**Table 3:** Descriptive statistics (mean and standard deviation) and statistical differences across fodder crop production clusters (CCL). Different subscripts indicate statistical significance ( $p < 0.005$ ). UAA utilized agricultural area.

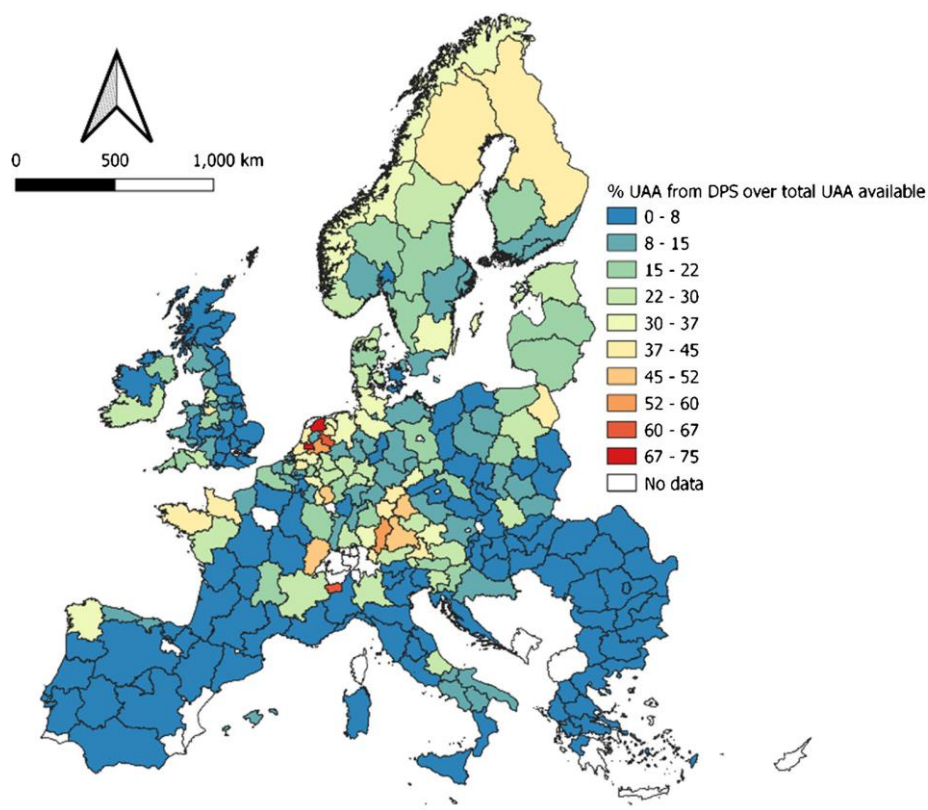
Fodder crop production clusters (CCL)	Cluster 1 (n=15)	Cluster 2 (n=57)	Cluster 3 (n=113)	Cluster 4 (n=30)	Cluster 5 (n=36)	Chi <sup>2</sup>	p-value
Share of permanent grasslands over the total UAA of the region	0.16±0.117 <sup>c</sup>	0.71±0.147 <sup>a</sup>	0.24±0.130 <sup>c</sup>	0.28±0.136 <sup>b</sup>	0.28±0.144 <sup>bc</sup>	134.6	<0.001
Share of temporary grasslands over the total UAA of the region	0.51±0.167 <sup>a</sup>	0.06±0.061 <sup>b</sup>	0.05±0.059 <sup>b</sup>	0.08±0.074 <sup>b</sup>	0.02±0.024 <sup>c</sup>	64.8	<0.001
Share of green maize over the total UAA of the region	0.001±0.0031 <sup>c</sup>	0.023±0.0276 <sup>b</sup>	0.027±0.0261 <sup>b</sup>	0.162±0.0506 <sup>a</sup>	0.040±0.0375 <sup>b</sup>	106.9	<0.001
Share of leguminous crops over the total UAA of the region	0 <sup>d</sup>	0.004±0.0064 <sup>c</sup>	0.008±0.0069 <sup>b</sup>	0.007±0.0085 <sup>b</sup>	0.040±0.0112 <sup>a</sup>	130.9	<0.001



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 1). 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 1:** Percentage (%) of utilized agricultural area (UAA) for specialized dairy farms over total UAA. DPS dairy production systems



### 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.

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 2). 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 2).

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 1). 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**

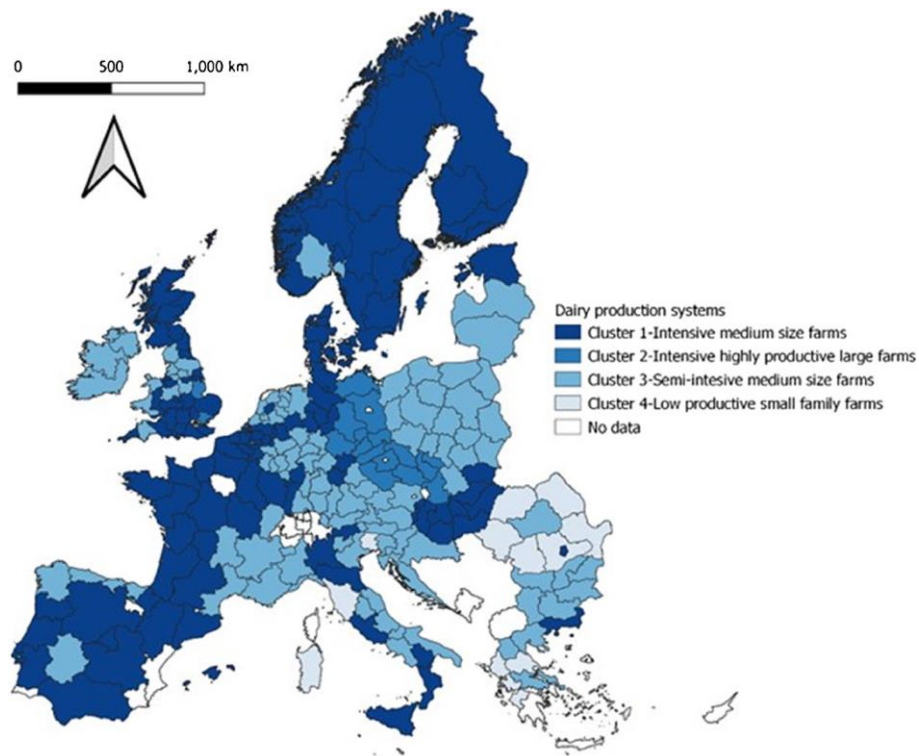
To date, previous studies have highlighted the need to move towards more sustainable farming systems across the three sustainability pillars (Duval et al. 2021; Helfenstein et al. 2022). In this

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.

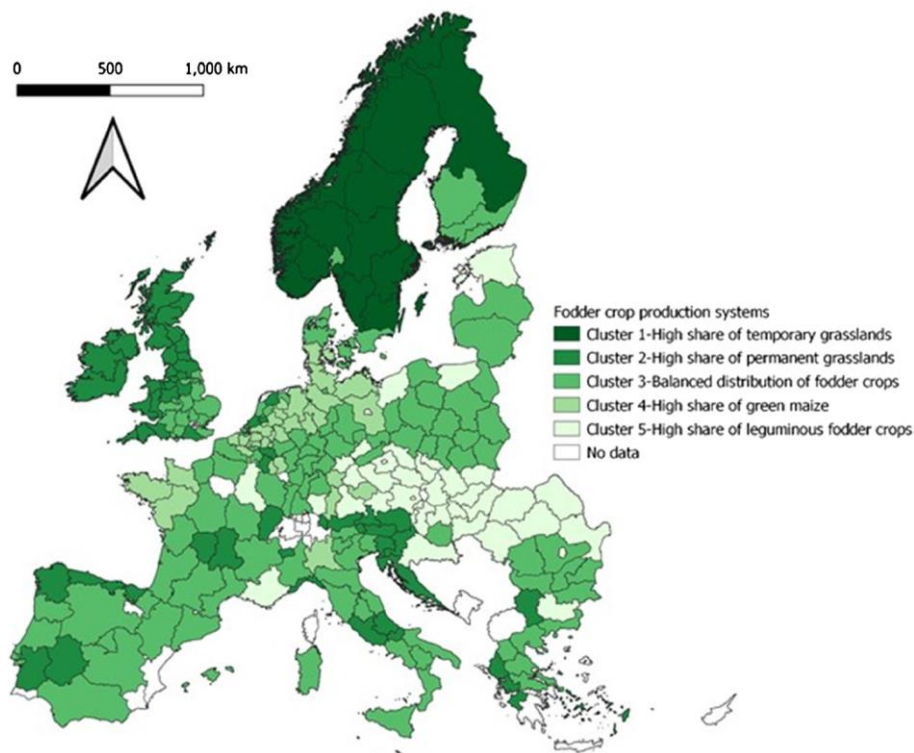
Although there is currently no individual indicator that analyzes the degree of specialization in milk production of European NUTS2 regions, concrete proxies can be used to assess it. By analyzing the share of total UAA dedicated to dairy cattle specialist farms, the degree of regional specialization 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.

**Figure 2:** Geographical distribution of the different dairy production system clusters (CL) (a) and fodder crop production system clusters (CCL) (b)



a) Clusters for dairy production systems



b) Clusters for fodder crop production systems

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).

**Table 4:** Mean, standard deviation (SD), minimum (Min), and maximum (Max) values of the share of UAA associated with dairy specialist farms over the total UAA for each of the dairy production system (DPS) clusters (CL) identified

DPS cluster (CL)	UAA specialization (%)			
	Mean	SD	Min	Max
CL1 (n=116)	12.8	12.12	0.2	42.5
CL2 (n=17)	9.8	7.94	0.7	31.4
CL3 (n=105)	20.7	17.30	0.3	74.6
CL4 (n=13)	2.1	1.89	0.2	5.8

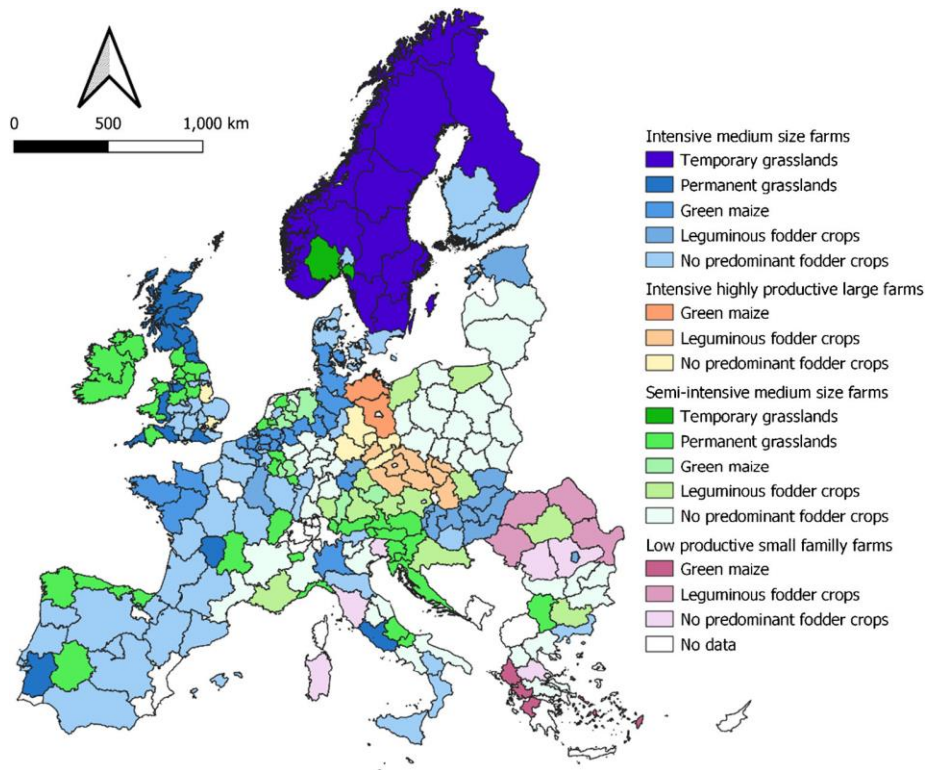
Lower levels of regional specialization could be observed in CL2 and CL4 with 9.8 and 2.1% of the total available UAA oriented to milk production, respectively (Table 4). Regarding the distribution of fodder crops in the clusters, large areas of these regions overlap with CCL3 (i.e., 41.2% for the CL2 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 3). 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 3:** Geographical distribution of the combined assessment of the different dairy and fodder crop production system



### 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.

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# **Chapter 5: Influence of farm diversity on nitrogen and greenhouse gas emission sources from key European dairy cattle systems: A step towards emission mitigation and circularity**

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## **Abstract**

European dairy cattle production systems (DPS) are facing multiple challenges that put their social, economic, and environmental sustainability at risk. In this sense, applying concepts, measures, and strategies to reduce nutrient losses and emissions is vital to ensure the sector's sustainability and facilitate the reconnection between crop and livestock systems. However, the success of these measures depends on their adaptation to particular characteristics and production contexts. In the absence of appropriate evaluation frameworks, the great diversity of DPS across Europe can challenge the effectiveness of these measures. For this reason, this study aims to analyze the influence of selected management practices and structural characteristics on the most significant nitrogen (N) and greenhouse gas (GHG) emission sources from ten key DPS across Europe. Furthermore, this research aims to support the application of circularity practices for dairy production by favouring better crop-livestock integration across key European DPS. To this end, whole-farm models and multivariate statistical methods are applied. The combined assessment of qualitative and quantitative farm characteristics and N and GHG emission sources facilitates a better understanding of the sources of emissions and nutrient losses while allowing for the future implementation of adapted and targeted mitigation and circularity measures. This study shows the relevant influence of climatic characteristics on N and GHG emissions associated with manure and fields. Similarly, when associated with intensive production systems, diet, herd management, and fertilization practices, reduced enteric emissions while increasing those related to housing, manure, and fields. Likewise, we demonstrated the direct relationship between the presence of high-emitting practices (i.e., open slurry tanks and broadcast slurry application) and N and GHG emissions. Furthermore, the potential of the evaluated DPS for a better integration between production systems was assessed. From a policy perspective, our results contribute to designing, implementing, and monitoring future context-specific emission mitigation and circularity measures by analyzing the contribution of DPS attributes to their most relevant emission sources. A better knowledge of these interactions could lead to implementing optimized practices and promoting integrated systems by recoupling of crop and livestock.

**Keywords:** Dairy production, nitrogen, greenhouse gas, circularity, recoupling, and crop-livestock.

## 1. Introduction

The challenges that the world's agri-food production sector currently faces require implementing integrated strategies that consider the economic, social, and environmental aspects of sustainability (FAO 2014). In recent years, reducing the negative impact of livestock production and favouring the protection of the environment has been one of the main cornerstones of European agricultural policies (Casey and Holden 2005; European Commission 2020; Guyomard et al. 2021). This reduction has to be accompanied by sustained production, ensuring adequate food supply and global food security (Peña-Lévano et al. 2019). In this context, ruminants provide society with products of high nutritional value (i.e., meat, milk, and its derivatives) obtained from feedstuff not digestible by other monogastric animals and impossible to get from plant-based foods (Leroy et al. 2022). Likewise, higher input prices (i.e., mineral fertilizers) increase the value of livestock sub-products, placing them as more circular nutrient sources (Glover et al. 2023). Given the number and complexity of the challenges faced by dairy cattle production systems (DPS) across Europe, it is necessary to provide adapted solutions considering the sector's diversity when implementing mechanisms to improve its sustainability (Díaz de Otálora et al. 2022).

Global agricultural intensification led and is further leading to the specialization of production systems by reducing the number of farms and increasing their size (Tilman et al. 2002; Hanson and Hendrickson 2009). In addition, this process derives in severe changes in land use due to a transition from diverse natural ecosystems to simplified cropping systems and even monoculture (Tschardt et al. 2005). This contributes to the decoupling of crop and livestock production systems, thus limiting their potential for diversification and increasing their dependency on external inputs (e.g., concentrates and mineral fertilizers) (Garrett et al. 2020). In this context, many studies have highlighted the positive consequences that recoupling these systems could have on the sustainability of the livestock systems (Ryschawy et al. 2012; Taifouris and Martín 2022). Moreover, reconnected systems can reduce production costs while improving land-use efficiency and crop yields (Low et al. 2023). However, the optimized implementation of circular practices requires their adaptation to current production systems. For this reason, developing appropriate methodologies and approaches is necessary to facilitate the unlocking of integrated practices that allow for the development of mixed crop-livestock production systems.

The intensification of the dairy cattle production sector has evident effects on its emissions (Clay et al. 2020). Livestock production in general and DPS in particular, are responsible for a large part of the agricultural sector's greenhouse gas (GHG) emissions and nutrient losses. In this



context, 14.5% of anthropogenic GHG emissions come from the livestock sector (Gerber et al. 2013), of which 20% are directly associated with milk production, representing 2.7% of the total (Tricarico et al. 2020). As for ammonia (NH<sub>3</sub>), 64% of global emissions are associated with animal production, with dairy production being one of the most significant sources of nutrient loss (Hristov et al. 2011; Sanchis et al. 2019). Feed supply (i.e., production and transport), enteric fermentation, as well as manure and field management, represent the most relevant sources of methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), and NH<sub>3</sub> from DPS. Therefore, it is necessary to identify practices that cause a more significant impact on the environment to efficiently reduce their harmful effect without compromising productive performance (Grainger and Beauchemin 2011). With this objective and aiming to meet current policy requirements, adopting emission mitigation concepts, strategies, and options is necessary (Ahmed et al. 2020). However, their optimal design and implementation present multiple challenges requiring a deep understanding of the interactions between different DPS components.

Using whole-farm models to assess emissions is a good compromise between accuracy and feasibility, considering the higher economic costs associated with direct on-farm emission measurements. While empirical approaches, based on simple methodologies using default values (Tier 1), are adequate to provide a general indication of emission trends, process-based models allow for the detailed simulation of existing dynamics inside the DPS. These tools consider climatic, environmental, land use, or management attributes (Tier 2) in specific scenarios (Calvo et al. 2019). In addition, process-based whole-farm models allow for the assessment of multiple interactions through the analysis of detailed physical-chemical processes commonly not assessed by empirical approaches (Xu et al. 2019). Among the various models available, SIMS<sub>DAIRY</sub> (Sustainable and Integrated Management Systems for Dairy Production) analyzes different loops and synergies between farm management, climatic conditions, and environmental characteristics on a monthly time step. As a result, this dynamic model evaluates the interactions between different farm components on GHG emissions and nutrient losses from animals, manure management, housing, and the fields (Del Prado et al. 2011; Rotz 2018). Moreover, SIMS<sub>DAIRY</sub> incorporates emission factors derived from higher-tier methods (Tier 2) and advanced models, allowing for a detailed analysis of the main drivers for emission reduction in a wide range of DPS typologies.

As for now, scientists and policy-makers have relied on many tools to determine and monitor the effect of different management practices on GHG and N emissions from DPS. However, the suitability and system response of mitigation options highly depend on each DPS's intrinsic

characteristics (Del Prado et al. 2010). The combination of different management practices and farm characteristics largely conditions emissions and their sources, as well as the potential for circular practices (e.g., using manure as organic fertilizers or cultivating legume and other fodder crops for livestock production). For this reason, identifying and assessing the influence of structural, climatic and farm management characteristics (i.e., temperature, diets, animal numbers, fertilizer application, manure storage typologies, etc.) will allow for a better adaptation and tailoring of future measures to be applied. This study aims to evaluate the effect of climatic and farm characteristics, manure management options, and mineral fertilization strategies on the main on-farm GHG and N emission sources from manure management, animals, housings and fields in key DPS across Europe. To this end, the whole-farm SIMS<sub>DAIRY</sub> modelling approach and multivariate statistical procedures that consider in a joint manner quantitative and qualitative indicators will be applied. This paper indicates appropriate ways to develop practices that better integrate crop and livestock systems while reducing on-farm N and GHG emissions.

## **2. Materials and methods**

### **2.1. Farm description and characteristics**

Ten European case studies farms for dairy production sector were selected. Even though some of the assessed DPS had beef-fattening enterprises, all were considered specialist dairy farms, as more than two-thirds of their standard output was from the dairy enterprise. These represent key DPS from Germany, Poland, Italy, France, Norway, and Ireland. The most relevant characteristics and management practices for each case study were collected in detail for the accounting year 2020. All data requirements, apart from on-farm climatic conditions, were obtained through individual in-depth interviews with farmers. The above-mentioned climatic characteristics were obtained from national meteorological agencies for the nearest meteorological station to the farm. The most relevant farm attributes for this study are shown in Table 1.

**Table 1:** Main features of the 10 dairy production systems analyzed. UAA: utilized agricultural area; ha: hectares; LU: livestock units; kg: kilograms; %: percentage, N: nitrogen. <sup>a</sup> Based on the Köppen climate classification, <sup>b</sup> over the total utilized agricultural area, <sup>c</sup> of the total dry matter, <sup>d</sup> both to arable crops and grasslands, <sup>e</sup> only self-produced concentrate.

	System	Climate <sup>a</sup>	Surface ha of UAA	Total animals LU	Total milk Production kg milk animal <sup>-1</sup> day <sup>-1</sup>	Stocking rate <sup>b</sup> LU ha <sup>-1</sup>	Grazing days days year <sup>-1</sup>	Purchased diet <sup>c</sup> %	Total mineral fertilizer <sup>d</sup> kg N ha <sup>-1</sup>
West Germany	Conventional	Temperate humid	71	174	30.7	2.5	0	30	85
East Germany	Organic	Temperate humid	230	129	20.1	0.6	273	18	0
North Germany	Organic	Cold humid	497	311	21.2	0.6	215	20 <sup>e</sup>	0
West Ireland	Conventional	Temperate humid	87	250	15.1	2.9	265	12	43
South Ireland	Conventional	Temperate humid	89	170	16.9	1.9	237	21	58
Central Norway	Conventional	Cold humid	87	91	21.5	1.2	139	43	128
North Norway	Conventional	Cold humid	30	41	22.1	1.4	91	28	109
North Italy	Conventional	Temperate humid	260	956	29.6	3.7	0	48	96
North Poland	Conventional	Cold humid	80	83	24.4	1.0	164	19	43
Central France	Conventional	Temperate humid	161	110	15.3	0.7	212	12	7

Regarding the three German case studies, both conventional and organic DPS were analyzed. In terms of surface, measured in utilized agricultural area (UAA), the conventional farm located in Northern Germany was the largest (497 ha), followed by the organic farms in the east and north, with 230 ha and 71 ha, respectively. As for the animal numbers, the largest analyzed DPS was located in the north with 311 livestock units (LU) (organic), followed by the farm in the west with 174 LU (conventional), and the one in the east (127 LU) (organic). The highest productivity among evaluated German DPS was shown in the conventional intensive farm, with a high stocking rate and a higher proportion of purchased fraction in the diet. This DPS achieved 31 kg milk animal<sup>-1</sup> day<sup>-1</sup>. Furthermore, this DPS was the only German case study that applied mineral fertilizer (85 kg N ha<sup>-1</sup>), while grazing was only performed in the Northern and Eastern farms.

As for the two Irish farms analyzed, one was located in the west of the country and the other in the south. Both the western and southern DPS had similar surfaces (87 and 89 ha), milk productivities (15 and 17 kg milk animal<sup>-1</sup> day<sup>-1</sup>), and grazing days (265 and 237 days year<sup>-1</sup>). However, significant differences were noted in animal numbers. The farm in the west of Ireland was larger than that in the south (250 vs. 170 LU). This resulted in concomitant differences in stocking rates, ranging from 2.9 LU ha<sup>-1</sup> in the western to 1.9 LU ha<sup>-1</sup> in the southern DPS. Likewise, notable differences were found in the purchased fraction of the diet and the use of mineral fertilizer, which were higher in the southern Irish DPS (30 vs. 12% and 58 vs. 43 kg N ha<sup>-1</sup>). Furthermore, the farm located in the south of the country had a beef fattening enterprise representing 14% of the total farm economic output.

The farm located in Northern Norway had a smaller surface (30 ha) compared to the central one (87 ha), as well as a lower animal number (91 LU vs. 41 LU). In addition, although milk production and stocking rates were similar in both DPS (22 vs. 21.5 kg milk animal<sup>-1</sup> day<sup>-1</sup> and 1.2 vs. 1.4 LU ha<sup>-1</sup>), the farm located in the center of the country had 139 days of grazing per year, while in the northern DPS, 91 days of grazing per year were registered. Likewise, significant differences were observed in the purchased fraction of the diet and in mineral fertilizer application, which was higher in the central Norwegian DPS than in the northern one (43 vs. 28% and 128 vs. 109 kg N ha<sup>-1</sup>). Moreover, the first of the farms located in Northern Norway had fattening cows accounting for 25% of the farm earnings.

As for the countries with a single case study, the farm in the north of Italy presented the largest surface and animal number compared to the DPS in central France and northern Poland (260 vs. 161 and 80). Likewise, the Italian DPS was the most productive of the three, showing the highest stocking rate (3.7 LU ha<sup>-1</sup>), the highest share of purchased feed (48%), and the most prominent

use of mineral fertilizer ( $96 \text{ kg N ha}^{-1}$ ). Furthermore, while the Polish and French DPS performed grazing (164 and 212 days year<sup>-1</sup>), the Italian DPS presented an all-year-round housed system.

As for the indicators used to characterize the effect of different management practices and structural characteristics on GHG and N emission sources, these were divided into quantitative and qualitative. Their description is based on the RAMIRAN glossary (Pain and Menzi 2011) (Table 2). The values/features recorded for each indicator by DPS are shown in Supplementary Material 1. The annual average temperature, wind speed, and amount of precipitation were used for describing the “climatic characteristics” of each DPS. Animal numbers, milk production, length of the housing period for adult animals, and stocking rates were gathered in the "herd management" category. As for the "diet characteristics", the fraction of purchased feed in the diet and the share of forage maize supplied over the total forage were utilized. In addition, multiple characteristics of the purchased diet were included in the “diet composition” category, such as digestibility, metabolizable energy, gross energy, crude protein (CP), and neutral detergent fiber (NDF) content. Regarding the “manure and mineral fertilizer”, the share of both slurry and farmyard manure (FYM) over total manure generated on the farm and the amount of mineral fertilizer applied to grasslands and crops ( $\text{kg N ha}^{-1}$ ) were recorded. Lastly, concerning the qualitative characteristics, these were divided into three categories. (i) "slurry application" techniques, (ii) "slurry storage covers", (iii) "mineral fertilizer" typology (i.e., urea, ammonium nitrate, etc.).

**Table 2:** Indicators included in the analysis. °C: degree centigrade; m: meters; s: seconds; mm: millimetres; LU: livestock units kg: kilograms; %: percentage; MJ: megajoules; DM: dry matter; N: nitrogen.\* Definitions extracted from the RAMIRAN Glossary

Indicator	Unit	Abbreviation	Explanation
Climatic characteristics			
Average temperature	°C	Temp	Average annual ambient temperature
Average wind speed	m/s	Wind	Average annual wind speed
Average precipitation	mm	Rain	Average annual precipitation
Herd management			
Animal numbers	LU	Animals	Total number of adult animals in the farm
Milk production	kg animal <sup>-1</sup> day <sup>-1</sup>	Milk	Average milk production per animal per day
Length of housing period	Days	HousDays	Number of days that adult animals are housed
Stocking rate*	LU ha <sup>-1</sup>	Stock	Number livestock units per unit area of total utilized agricultural area
Diet composition			
Fraction purchased feed in the diet	%	Feed	Fraction of the total diet (in DM) composed of purchased or off-farm produced feed
Share of forage maize supplied	%	Maize	Fraction of the total forage supply composed by maize silage
Characteristics purchased diet			
Digestibility	%	Diges	Digestibility of the purchased fraction of the diet
Metabolizable energy	MJ kg DM <sup>-1</sup>	EnMet	Metabolizable energy content of the purchased fraction of the diet
Gross energy	MJ kg DM <sup>-1</sup>	EnGross	Gross energy content of the purchased fraction of the diet
Crude Protein	%	CP	Crude protein content of the purchased fraction of the diet
Neutral detergent fiber	%	NDF	Neutral detergent fiber content of the purchased fraction of the diet
Manure and mineral fertilizer			
Share of slurry	%	Slurry	Fractions of the dejections handled as slurry over total manure production
Share of farmyard manure	%	FYM	Fractions of the dejections handled as farmyard manure over total manure production
Mineral fertilizer applied	kg N ha <sup>-1</sup>	FertQuan	Amount of mineral/inorganic fertilizer applied per hectare
Slurry application			
Broadcast*	-	Broadcast	Slurry spread over the whole surface of an area of land or crop
Injection*	-	Injection	Slurry application by placing it placement in slots cut into the soil to various depths
Slurry covers			
No cover	-	Open	Crustless open slurry storage tank
Crust*	-	Crusted	A fibrous floating layer that forms on the surface of stored slurry
Rigid cover*	-	Rigid cover	A structure fitted to a slurry store mainly
Mineral fertilizer typology			
No mineral fertilizer	-	No	No mineral fertilizer is applied to the fields or crops
Urea	-	Urea	Urea is applied to the fields or crops
Ammonium nitrate	-	AN	Ammonium nitrate is applied to the fields or crops
Calcium ammonium nitrate	-	CAN	Calcium ammonium nitrate is applied to the fields or crops

## 2.2. Emission source modelling

Emission sources from the different DPS presented in this work were estimated using the SIMS<sub>DAIRY</sub> modelling framework. This model is one of the existing tools at the farm scale oriented towards the assessment of GHG emissions and N losses associated with the different dairy production (Schils et al. 2007; Del Prado et al., 2013; Díaz de Otálora et al. 2021). While this model was initially developed to analyze mostly pasture-based systems (Ahmed et al. 2020), the updated version allows for analyzing a wide range of DPS, including intensive farms without grazing. The empirical and dynamic nature of SIMS<sub>DAIRY</sub> enables capture of internal interactions and loops between farm components and climatic characteristics (i.e., temperature, rainfall, wind speed) (Del Prado et al. 2011). This feature is crucial to observe how adjusting or implementing specific attributes or management practices can have opposite effects on different N and GHG emissions.

SIMS<sub>DAIRY</sub> simulates the monthly emissions of CH<sub>4</sub>, N<sub>2</sub>O and nitrogen oxides (NO<sub>x</sub>), CO<sub>2</sub>, NH<sub>3</sub>, and losses of nitrates (NO<sub>3</sub><sup>-</sup>) associated with different subsystems of a DPS. The model covers the entire production year. Specifically, the latest version of the model employs the methodology derived from the Intergovernmental Panel on Climate Change (IPCC) 2019 refinement for determining CH<sub>4</sub> emissions from enteric fermentation and manure management (Gavrilova et al. 2019). Regarding N losses, SIMS<sub>DAIRY</sub> applies a mass balance approach based on total ammoniacal N content and tailored emission factors for each manure management stage to determine the most relevant emissions (i.e., N<sub>2</sub>O, NH<sub>3</sub>, and NO<sub>x</sub>) (Webb and Misselbrook 2004). Furthermore, NO<sub>3</sub><sup>-</sup> leaching and N<sub>2</sub>O field emissions are based on the NGAUGE modelling approach, which jointly simulates the N flows from plant uptake, denitrification, nitrification, and mineralization processes, along with the meteorological conditions, soil texture, fertilization, and grazing patterns (Brown et al. 2005).

Determining emissions from the different farm subsystems is necessary when designing and implementing emission mitigation strategies adapted to the particular characteristics of each DPS. In order to obtain an overview of these emissions, we grouped them according to their different sources. In the case of GHG emissions (direct and indirect), these were divided into three sources: enteric fermentation, manure management (housing and storage), and in field emissions. CH<sub>4</sub> was the only gas considered for enteric fermentation. For manure management, both CH<sub>4</sub> and N<sub>2</sub>O were included. Finally, GHG emissions from fields consisted of N<sub>2</sub>O. As for N emissions, these were grouped into five sources: housing, fields, storage, yards, and silage. The magnitude of each source was determined by adding up all modelled gases (N<sub>2</sub>O, NH<sub>3</sub>, NO<sub>3</sub><sup>-</sup>

, and NO<sub>x</sub>). In this study, emissions were represented per kg of raw milk. CH<sub>4</sub> and N<sub>2</sub>O emissions were converted to CO<sub>2eq</sub> using the 100-year Global Warming Potential (GWP-100) values of 27.2 (non-fossil fuel CH<sub>4</sub>) and 273 (N<sub>2</sub>O) according to the latest Sixth Assessment Report (AR6) of the IPCC (Forster et al. 2021).

### **2.3. Statistical analysis**

The influence of different management practices and structural characteristics on N and GHG emission sources was analyzed using a statistical procedure capable of jointly assessing quantitative (continuous) and qualitative (categorical) variables. At the same time, this approach supports identification of potential practices to increase crop-livestock integration and reduce nutrient losses. For this work, we opted for a multivariate approach, which allows for the analysis of simultaneous observations of several variables (Good 2005). Compared to statistical procedures commonly used for this type of data, such as Factor Analysis (FA) or Principal Component Analysis (PCA), the Factor Analysis for Mixed Data (FAMD) can incorporate both quantitative and qualitative variables in the same algorithm, thereby jointly analyzing the similarity between them (Pages 2004). Although previous authors have used FAMD to detect anomalies in large databases (Davidow and Matteson 2022), in this article, the objective was to develop new linear combinations (dimensions) by accumulating the variance of initial variables (qualitative and quantitative). In this way, we were able to check which variables were grouped to create these combinations and analyze their degree of influence on emission sources.

Before the FAMD application, the original database was refined to make it suitable for statistical analysis. First, given the differences observed in the units of quantitative variables (Table 1), these were normalized according to their mean and standard deviation. Second, qualitative variables, originally inputted as "characters" or categorical variables, were transformed into "factors" (format accepted by the FAMD algorithm). Third, independent variables (variable whose variation does not depend on that of another), such as management practices and structural characteristics, were included in the statistical procedure as principal variables. Lastly, the response of dependent indicators (i.e., GHG or N emission sources) was excluded from the analysis but as inputted as supplementary variables. As described in previous studies using similar statistical procedures, analyzing the supplementary variables with the same statistical method as the independent variables could facilitate a better interpretation of obtained relations (Abdi and Williams 2010). This is a common procedure in cases when the response variables are determined from independent variables to some extent, thus avoiding possible interferences in the analysis. Then, these variables were plotted in the factorial space using the same formulas



applied to the active ones. In this way, their relationship with other analyzed indicators could be observed.

All data was analyzed using the R statistical software (R Core Team 2022). The FAMD() function included in the "FactorMineR" package was used to perform the analysis (Le et al. 2008). Graphs presented in this work were obtained in R by using the functions of the "Factoextra" package (Kassambara and Mundt 2020).

### **3. Results**

#### **3.1. Emissions from key sources**

Regarding GHG emission sources, the highest value was observed in Northern Italian DPS (1.1 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>). In contrast, the lowest value was attributed to the conventional Western German farm with 0.5 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>). The individual results for each GHG source showed that enteric fermentation accounted for the largest share of emissions in all case studies. The highest value was obtained on the central French farm with 0.6 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, while the conventional western German case study presented the lowest value (0.3 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>). In the case of the emission intensity from manure management (i.e., CH<sub>4</sub> and N<sub>2</sub>O), the highest value was noted in the Italian DPS, while the farm in North Norway presented the lowest value (0.3 vs. 0.1 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>). Finally, the N<sub>2</sub>O emission intensity of fields varied significantly among the DPS under study. Notably, the highest value was achieved in the Northern Polish farm with 0.4 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, while the lowest value was obtained in Western conventional German DPS with 0.03 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>.

**Table 3:** Results for greenhouse gas (GHG) and nitrogen (N) emission intensity for the different dairy production systems (DPS) modelled with the SIMS<sub>DAIRY</sub>. DPS: dairy production system; kg: kilograms; CO<sub>2</sub>: carbon dioxide; N: nitrogen; g: grams.

	GHG emission intensity				N emission intensity					
	kg CO <sub>2eq</sub> kg milk <sup>-1</sup>				g N kg milk <sup>-1</sup>					
	Enteric	Manure	Fields	Total	Fields	Housing	Silage	Yards	Storage	Total
West Germany	0.32	0.18	0.03	0.53	4.13	1.52	1.30	0.76	0.57	8.28
East Germany	0.42	0.07	0.07	0.56	5.52	0.41	0.73	0.30	0.10	7.06
North Germany	0.43	0.10	0.05	0.58	3.43	0.57	1.01	0.24	0.30	5.55
West Ireland	0.53	0.09	0.07	0.69	3.33	0.46	0.69	0.32	0.28	5.08
South Ireland	0.52	0.10	0.31	0.93	6.27	0.59	0.95	1.18	0.26	9.25
Central Norway	0.45	0.12	0.16	0.73	8.04	1.07	1.64	0.92	0.44	12.11
North Norway	0.46	0.06	0.10	0.62	2.40	0.95	2.22	0.97	0.64	7.18
North Italy	0.48	0.31	0.31	1.14	8.57	1.20	1.10	0.61	0.60	12.08
North Poland	0.41	0.24	0.38	1.03	3.92	1.09	0.92	0.42	0.92	7.27
Central France	0.59	0.13	0.27	0.99	11.18	0.67	1.30	1.22	0.73	15.10

As for the intensity of N emission sources (i.e.,  $\text{NH}_3$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_3^-$  and  $\text{NO}_x$ ), the highest value was observed in the Central French farm, while the lowest value was obtained in the Western Irish DPS, with 15.1 and 5.1 g N kg milk<sup>-1</sup>, respectively. The modelling of the different emission sources shows that the highest N losses were associated for fields. In this case, the highest value was observed in the Central French case study, while the lowest value was attributed to the organic Northern Norwegian one with 11.2 and 2.4 g N kg milk<sup>-1</sup>, respectively. The highest emissions associated with the housing stage were noted in the Western German DPS (1.5 g N kg milk<sup>-1</sup>). In contrast, the lowest emissions were obtained in the Eastern German organic DPS with 0.4 g N kg milk<sup>-1</sup>. Regarding N emissions derived from silage, there were evident differences among DPS, ranging between 2.2 g N kg milk<sup>-1</sup> in the Northern Norwegian farm and 0.7 g N kg milk<sup>-1</sup> in the Western Irish farm. On the contrary, emissions derived from yards presented a lower variation, with the highest value obtained in the South of Ireland (1.2 g N kg milk<sup>-1</sup>) and the lowest in the Northern organic German farm (0.2 g N kg milk<sup>-1</sup>). Finally, the highest N emissions from manure storage were recorded in the Northern Polish farm, with 0.9 g N kg milk<sup>-1</sup>. Conversely, the organic Eastern German DPS presented the lowest value for this N emission source (0.1 g N kg milk<sup>-1</sup>).

### **3.2. Dimension construction and DPS contribution**

As shown in Table 4, the results obtained from the FAMD application show that the first two dimensions cumulated 50% of the variance of the qualitative and quantitative variables included in the analysis. The first two dimensions represented 27.3% and 22.5% of the total variance of the analyzed sample. These dimensions were subsequently used to determine the relationship between management practices, structural characteristics, and GHG and N emission sources. In addition, Table 4 presents the contribution of each category of quantitative and qualitative variables to the dimensions identified after applying the FAMD method by adding up the individual contributions of indicators in these categories. The contribution of each indicator (qualitative and quantitative) can be found in Supplementary Material 2. Likewise, the individual contribution of the dimension is detailed in Supplementary Material 3.

Regarding the contribution of quantitative indicators to the first dimension (Dim1), herd management characteristics had the most prominent effect (38%), with the number of animals as the most relevant indicator (11%). To a lesser extent, the composition of the purchased diet had a notable effect on this dimension (16%). As for the contribution of the climatic characteristics (14%), the average temperature had a significant role, contributing by 8% to this dimension. Indicators associated with diet characteristics, and the manure and fertilizer presented a lower

weight in Dim1, 12 and 8%, respectively. Regarding quantitative indicators, the highest contribution to this dimension was observed for the slurry covers used (8%), with crust presenting the highest percentage (4%). As for the assessment of individual observations, the Italian DPS contributed the most to the first dimension (61%).

**Table 4:** Results obtained from the application of Factor Analysis for Mixed Data (FAMD) for the first and second dimension (Dim). The percentage (%) of contribution of each of the categories of indicators to these dimensions is also presented.

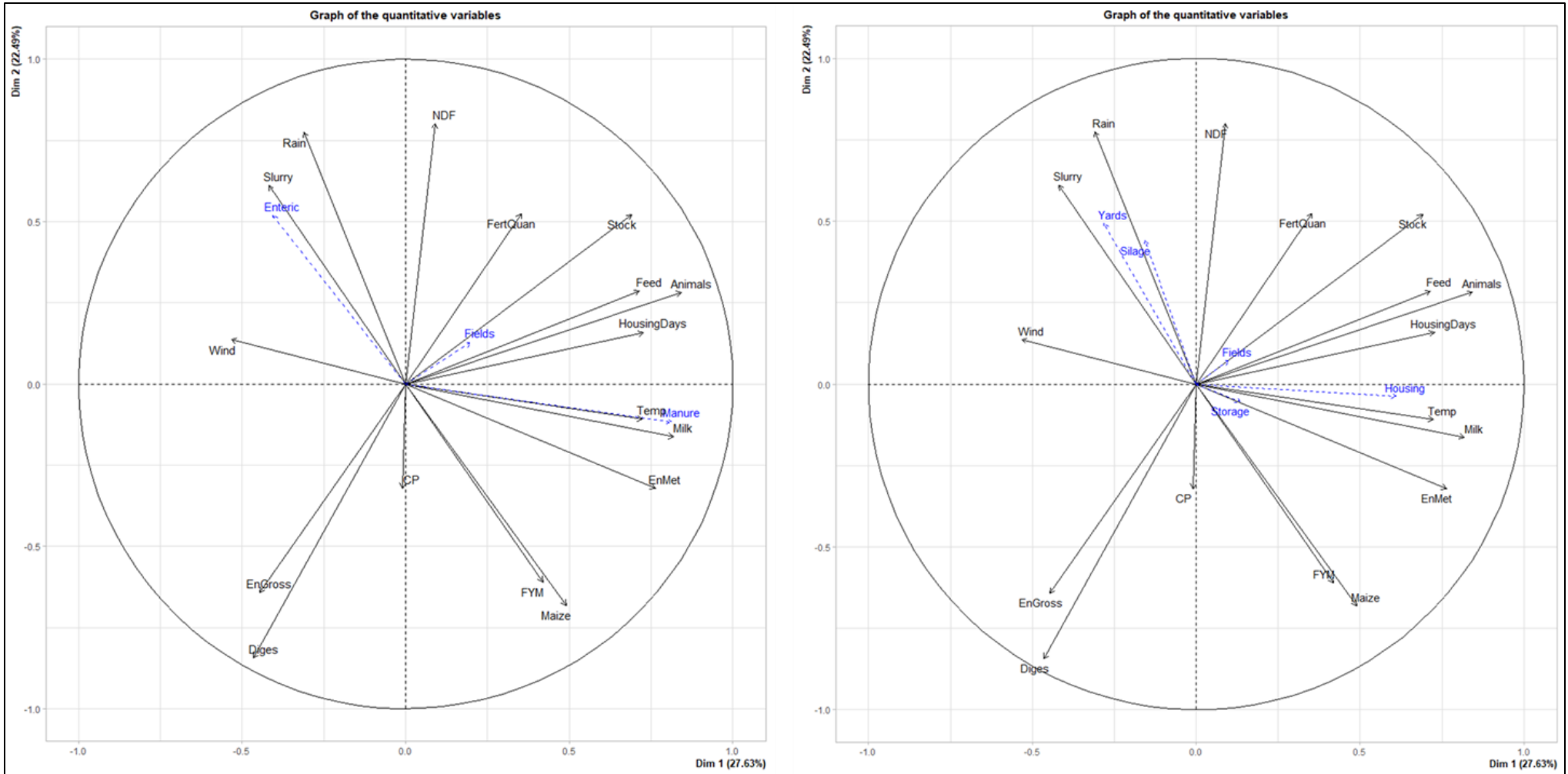
	FAMD	
	Dim 1	Dim 2
Variance	6.4	5.2
Cumulate % variance	27	50
	Contribution (%)	
Quantitative indicators		
Climatic characteristics	14	12
Herd management	38	8
Diet characteristics	12	11
Composition of the purchased diet	16	38
Manure and mineral fertilizer	8	20
Qualitative indicators		
Slurry application	0	1
Slurry covers	8	3
Mineral fertilizer typology	5	7

Regarding the contribution of quantitative variables to the second dimension (Dim2), a notable influence of the composition of the purchased fraction of the diet was observed (38%). In this regard, the digestibility (14%) and the NDF content (12%) were presented as the main contributors. Manure and mineral fertilizer indicators contributed to a lesser extent to this dimension with 20%. The rest of the quantitative variables presented lower values. In detail, the contributions obtained were 12% for the climatic characteristics, 11% for the diet characteristics and 8% for the herd characteristics. Regarding qualitative indicators, a contribution of 7% was observed for both the type of mineral fertilizer used with no mineral fertilizers contributing with 4%. Individual observations showed that Dim2 was more predominantly affected by the DPS located in Northern Norway (27%)

### 3.3. Effect of quantitative variables on GHG and N emission sources

Figure 1 shows the relationship between the different sources of GHG (a) and N (b) emissions and the quantitative variables included in the statistical analysis. The text below describes the most significant trends and relations between these emission sources and the evaluated structural and management characteristics.

**Figure 1:** Graphical representation of the quantitative indicators evaluated (black) as well as the main sources of GHG (left) and N (right) emission sources (blue) according to the first two dimensions. GHG: greenhouse gas; N: nitrogen; Dim: dimension; NDF: neutral detergent fiber; FertQuan: mineral fertilizer quantity; EnMet: metabolizable energy; Temp: temperature; HousDays: housing days; Stock: Stocking rate; FYM: Farmyard manure; CP: crude protein; EnGross: gross energy; Diges: digestibility.



Regarding the influence of analyzed variables on emissions intensity from enteric fermentation, a positive correlation was observed with slurry as the primary manure management option, mainly given the effect in the sample of grass-based systems with a high presence of slurry, and higher enteric emissions. Likewise, these results indicated that DPS with solid manure (i.e., farmyard manure) as the predominant manure management strategy accounted for lower emissions from enteric origin. Furthermore, enteric emissions were positively correlated with the NDF content in the diet, and the amount of fertilizer applied. On the contrary, higher digestibility and larger fraction of silage maize in the diet were inversely correlated with emission intensity from enteric fermentation.

In the case of CH<sub>4</sub> and N<sub>2</sub>O emission intensities related to manure management, a positive correlation was observed with the average annual ambient temperature. In addition, the higher metabolizable energy content in the purchased fraction of the diet, housing days and the number of animals resulted in higher emissions associated with this source. Moreover, manure-related GHG emissions were proportional to housing days and average milk production through a positive association. In contrast, climatic characteristics such as average wind speed and higher average precipitation throughout the year negatively affected manure emissions. Concerning N<sub>2</sub>O emissions intensity from fields, larger doses of mineral fertilizer and higher stocking rates were associated with higher field emissions. In contrast, higher digestibility and CP content were negatively associated with field emissions.

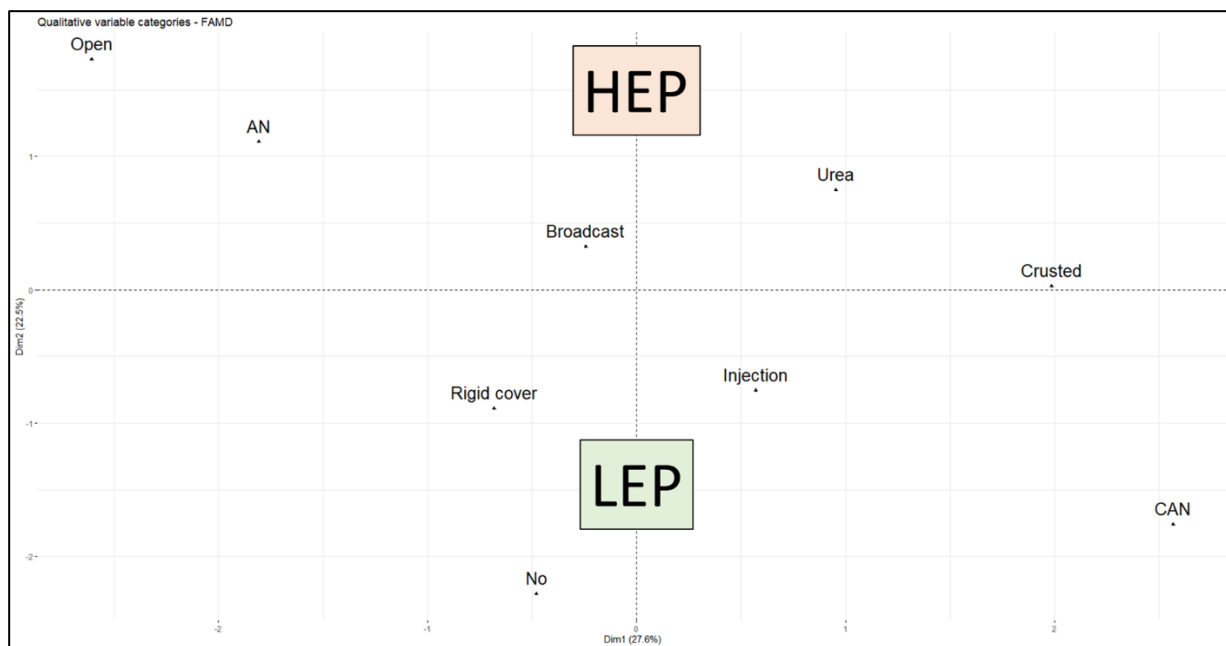
As for the effect of quantitative variables on N emission sources, a directly proportional relationship was observed between field N losses and higher mineral fertilization levels, the ratio of purchased feed in the diet, and stocking rates. Conversely, the increase in gross energy content, CP content, and digestibility values in the purchased fraction of the diet resulted in lower N emissions associated with manure storage, yards, and silage making. Climatic factors significantly influenced N emissions associated with housing and storage. Higher average annual ambient temperature was directly correlated with housing-related N emissions. Likewise, more housing days, more animals and higher milk production were associated with increased emissions. On the contrary, environmental attributes such as average wind speed had an inverse effect on this emission source. Finally, emissions derived from yards showed a similar trend to silage –related ones. These N emission sources presented a directly proportional correlation with slurry as the predominant manure management system and higher content of NDF in the purchased fraction of the diet. On the contrary, the presence of FYM as a manure management

system and a higher presence of silage maize inversely affected emissions generated from these sources.

### 3.4. Effect of qualitative variables on GHG and N emission sources

The distribution of the different management options (i.e., slurry application technologies, slurry tank covers, and the type of mineral fertilizer) with regard to identified dimensions is shown in Figure 2. GHG and N emission sources followed equal graphical representation as in Figure 1.

**Figure 2:** Spatial representation of the different management practices (qualitative variables) with respect to the first two dimensions obtained from the Factor Analysis for Mixed Data (FAMD). Dim: dimension; LEP: low-emitting practices; HEP: high-emitting practices; AN: ammonium nitrate; CAN: calcium ammonium nitrate; Injection: shallow injection of slurry; Broadcast; slurry application with broadcast Open: open slurry tank without cover; Crusted: open slurry tank with cover; Rigid cover; rigid cover of the slurry tank; No: no mineral fertilizer applied.



In order to analyze their effect on emission sources, these variables were grouped according to their potential emission level. This classification was based on the GHG and N emission potential associated with each of the different strategies considered in the study. Practices associated with higher emissions were categorized as "High-Emitting Practices" (HEP). Conversely, measures whose application is associated with lower GHG and N emissions were called "Low-Emitting Practices" (LEP). As shown in Figure 2, LEP grouped different strategies associated with using mineral fertilizer, slurry application technologies, and slurry storage covers. For these strategies, the non-use of mineral fertilizers (associated with organic DPS) or using CAN was contemplated. In addition, applying slurry by injection and rigid or crusted covers in slurry storage were identified as LEP. As for the HEP, applying AN as a mineral fertilizer, using broadcast as a slurry application technology and the absence of covers for the storage facilities were included. A

positive correlation was observed between HEP and higher emission intensity associated with enteric fermentation and field management regarding the effect of different management strategies on GHG emission sources. Regarding emissions from manure management (i.e., housing and storage), a positive correlation was observed between this source and crusted slurry tanks and urea and CAN as mineral fertilizers. Regarding the influence of different management practices on N emission sources, a positive correlation was observed between HEP and emissions derived from yards, silage production, the fields and manure storage. Lastly, N emissions from housing were associated with crusted slurry storage facilities and inversely associated with open slurry tanks and AN application.

## **4. Discussion**

### **4.1. Implications for adapted mitigation of on-farm emissions**

The variability in emission sources is a clear source of uncertainty in estimating the effect of emission mitigation measures from DPS (Zehetmeier et al. 2014). While previous studies have analyzed the effect of different production practices on the sustainability impact of DPS (van der Werf et al. 2009), a thorough understanding of the systems is necessary to ensure their success. Through a novel multivariate statistical approach, we allow for a joint assessment of quantitative and qualitative characteristics facilitating a better understanding of the effect that different structural characteristics and management options have on the most significant GHG and N emission sources of DPS. In this way, the adaptation of measures and decision-making at the farm level is facilitated. Furthermore, due to the multiple interactions between farm components, climatic conditions, and management options, DPS are presented as complex livestock systems (Stirling et al. 2021), thus requiring the adaptation of practices to specific regional contexts.

The observed relationship between high temperatures, housing days, and GHG and N emissions associated with manure management, housing and storage highlights the need to design adapted strategies for each particular context. The assessed relationships indicated that those DPS located in Mediterranean regions (i.e., Italian DPS) or intensive systems with large periods of housing (i.e., western German DPS) would benefit from options aimed at reducing manure storage times (i.e., more frequent application) or quick removal of the slurry from the barns (i.e., biogas plants or covered manure storages). As demonstrated by previous authors, these strategies are associated with lower GHG and N emissions during storage while increasing the nutrient availability of the digestate for future application as organic fertilizer (Sanz-Cobena et al. 2017; Cárdenas et al. 2021). Furthermore, increasing the ventilation rate inside the barn is an appropriate option in those in intensive farms located in warm climates (i.e., Mediterranean farms), deriving in a



reduction in NH<sub>3</sub> emissions during housing and an improvement in animal welfare (Sanchis et al. 2019).

Diets play a crucial role in modulating GHG emissions and nutrient losses from DPS (Peterson and Mitloehner 2021). Our results show how different feeding strategies based on pasture (i.e., extensive or semi-extensive systems), purchased feed (i.e., intensive systems), or a combination of both lead to variable emission levels. Diets associated with intensive farms (i.e., maize forage and concentrate) presented less enteric fermentation emissions compared to grass-based diets. These results align with existing literature, which associates greater diet digestibility, metabolizable energy content, and lower presence of NDF with lower emissions (Yan et al. 2010; Valencia-Salazar et al. 2021; Hristov et al. 2022). However, it is necessary to consider the effect of concentrate-based and highly-digestible diets from a holistic perspective. Improving diet composition without causing negative trade-offs in other emission sources (i.e., concentrate production) is crucial. Based on our results, improving the roughage quality (i.e., reducing grass maturity) in pasture-based systems could reduce field and enteric emissions (Van Middelaar et al. 2014), without adding external concentrate associated with higher off-farm emissions. This could be particularly relevant for those DPS located in regions where grazed grass is the main source of feed (i.e., Irish DPS). Furthermore, increasing the digestibility of the forage supplied (both purchased and self-produced) in those systems that use intensive concentrates (i.e., Italian and Western German DPS) reduces GHG and N emissions at the same time that decreases the dependency on external feed is reduced, thus mitigating potential off-farm CO<sub>2</sub> emissions.

Regarding the "herd management" options, more animals, higher stocking rates, and higher milk productivity are commonly associated with longer housing periods and more intensive farming systems (Meul et al. 2012). Our results show that the increase in these indicators is associated with a concomitant increase in GHG and N emissions from manure and housing. This increase is mainly associated with N<sub>2</sub>O and NH<sub>3</sub>, which are significantly higher in intensive systems than in farms with more grazing time (Hennessy et al. 2020). However, as noted by our results, pasture-based systems (i.e., more than 200 days on grazing) are associated with lower milk production (i.e., Irish and French farms). Therefore, increasing their production efficiency by optimizing grazing practices (i.e., timing, rational grazing, etc.) is a win-win strategy from both productive and sustainability perspectives (Shalloo et al. 2018). Furthermore, to keep high productive yields, intensive systems (i.e., Western German and Italian DPS) should focus on implementing structural improvements to mitigate the emissions related to housing. In this regard, the implementation of composting bedding materials and separating feces from urine, specifically in

farms with longer housing periods and intensive systems (i.e., Western German and Italian farms) (Galama et al. 2020).

Several studies highlighted the need to implement better practices related to manure management and mineral fertilizer application to reduce GHG and N emissions (Aguirre-Villegas and Larson 2017; Christie et al. 2020). In this context, our results contribute to a better understanding of the factors and practices associated with "manure and mineral fertilizer" that contribute most to such emissions, paving the way towards future design and implementation of tailored measures. As described by previous authors, the intensive use of mineral fertilizers and HEP are associated with increased GHG and N emissions from fields (Byrnes 1990; Duncan et al. 2017). In this context, substituting these practices with more efficient ones (e.g., CAN, protected urea, slurry injection) would be particularly relevant in farms with higher field emissions that largely rely on urea as mineral fertilizer (i.e., Italian and Southern Irish farms). Likewise, the inverse relationship observed between N emissions from manure storage, and the implementation of LEP (manure covers) was a clear indicator of the need to implement more efficient covers in storage facilities to reduce N emissions (Kupper et al. 2020). Therefore, optimized emission reductions could be achieved by applying these options to DPS with significant slurry production and large outside storages (i.e., Italian and Western German farms).

As for other emission sources, the results showed a direct relationship between N emissions from yards and slurry as the principal manure management system. In addition, an indirect relationship between N emissions from silage production (i.e., grass and maize) and the feeding of maize silage was observed. Regarding the association between yard emission and slurry, as recommended by previous authors, farms with extended housing periods (i.e., Italian and West German farms) and slurry systems could significantly benefit from frequent slurry removal to reduce these emissions (Misselbrook et al. 2006). In the case of silage emissions, previous authors associated the use of maize silage with lower nutrient losses compared to other types of forage (i.e., grass) (Köhler et al. 2013). To prevent these emissions, farms with higher N losses during silage production (i.e., Norwegian farms) should implement efficient ensiling practices and technologies to lower emissions (Krueger et al. 2023). Finally, in contrast to the previous literature (Ebertz et al. 2020), our results showed an inverse relationship between maize silage supply and slurry production. This may be due to the overrepresentation of grazing systems in our sample. In this sense, specific studies and a more significant number and diversity of observations would help further deepen obtained results.

## **4.2. Unlocking the potential for crop-livestock integration and circularity practices**

The current trend of livestock production concentration and intensification has led to undesirable environmental effects (Clay et al. 2020). These processes have caused significant land use changes and reduced ecosystem biodiversity and landscape diversity (Emmerson et al. 2016). In this context, the successful recoupling of crop and livestock systems could potentially reduce these adverse effects, promote circularity, and increase the overall sustainability of the sector (Tabacco et al. 2018). The proposed analysis allows for the identification of relationships between farm intensification characteristics (i.e., stocking rate, the amount of mineral fertilizer used, and the share of purchased diet) and N and GHG emissions better supporting the implementation of crop-livestock integration practices (i.e., efficient N practices).

Our results confirm that intensive systems are generally associated with lower emission intensities. However, these systems (i.e., Italian and Western conventional German farms) presented higher stocking rates, larger use of mineral fertilizers (oriented to grass and maize production), and a higher share of purchased feed in the diet (i.e., concentrates). These results indicate a decoupling between crop and livestock systems, thus leading, as confirmed by our results, to highly specialized and intensive farms (Jin et al. 2021), which contribute more to the sector's environmental impact. In addition, the lack of mixed systems favors the widening of nutrient cycles and the isolation of farmers (Martin et al. 2016). In this context, we contribute to a preliminary identification of contexts in which a greater integration between crops and DPS is suitable. In this sense, higher levels of crop-livestock integration and lower nutrient losses could be reached through better feeding strategies based on local or farm production and integrated management practices, and by considering farmyard manure and slurry from DPS as high-value organic fertilizers. In addition, although the model used does not evaluate the carbon sequestration derived from grazing, future consideration of this aspect would be crucial when analyzing the role of DPS in mitigating and offsetting emissions (Molossi et al. 2020; Whitehead 2020).

Although purchased feed (i.e., concentrates based on cereals) are commonly more digestible than forage (i.e., grass, maize, or alfalfa), they largely contribute to the food-feed competition and are one of the primary sources of off-farm CO<sub>2</sub> emissions associated with livestock production systems (Thomassen et al. 2008; Moreno et al. 2020). Providing quality forages (i.e., highly digestible) in substitution of concentrates could benefit DPS with a high rate of purchased feed (i.e., Italian, Central Norwegian, and Eastern German farms). Indeed, this would be associated with lower emissions (especially off-farm) and nutrient losses from fields and manure

management. Furthermore, the increase in production intensity requires the maintenance of high crop yields to produce enough feed for animals. In order to keep these high yields stable, the use of mineral fertilizers is widely spread throughout agricultural systems (Mason et al. 2022). The intensive fertilizer application has significantly contributed to the widening of nutrient cycles (i.e., N and phosphorus (P)) and reducing of soil organic matter (Menšík et al. 2018; Kronberg et al. 2021). Our results showed higher field-associated N and GHG emissions as mineral fertilizer increased. Therefore, promoting the connection between animals and crops through better manure valorization would reduce the dependency, mainly on urea, of these fertilizer-intensive DPS (i.e., Italian and Irish farms). This could simultaneously contribute to the recoupling of systems and better nutrient cycling. In this sense, farmyard manure and slurry from DPS have a great potential to be used as fertilizers from a biological origin (van der Wiel et al. 2021). Even if further research is needed better assess their role as organic fertilizers in different production contexts, they are widely used across Europe. Our results indicate that DPS with high slurry production and appropriate storage facilities are more suitable to use slurry as organic fertilizer in partial or total substitution of mineral fertilizer. The valorization of slurry as organic fertilizer allows for better system integration by recycling farm resources, reducing emissions and nutrient losses, while promoting circularity (Zhang et al. 2021; Menegat et al. 2022).

## **5. Conclusion**

Accounting for the diversity of DPS when designing, implementing, and evaluating N and GHG emissions mitigation options and circularity practices is crucial for ensuring their success. The variety of existing DPS throughout Europe allows for a better adaptation of strategies to optimize resource use and recoupling crop and livestock systems. In this study, this is done through a joint analysis of the influence of various management practices and farm structural characteristics on the most relevant sources of GHG and N on-farm emissions through a novel multivariate statistical approach capable of jointly assessing quantitative and qualitative indicators. The results supported not only the adaptation of emission mitigation measures but also the application of circularity practices.

Through a joint statistical analysis of quantitative and qualitative indicators, a better understanding of the effect of different management practices and structural features on modelled GHG and N emissions sources was facilitated. Likewise, the results highlighted the influence of climatic conditions, herd and manure management strategies, fertilizer application options, and diet compositions on animal, manure, housing, and field emissions. Furthermore, presented results identified key drivers and relations for the circularity of DPS, thus facilitating the

application of adapted mixed (crop-livestock) production patterns. In addition, future developments of the proposed framework should look at better accounting for off-farm emissions and circular practices, which contribute significantly to GHG and N emissions and the overall sustainability of DPS. In essence, further implementation of emission mitigation practices and greater promotion of integrated crop-livestock systems could drive the sector toward environmental, social, and economic sustainability.

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**Supplementary Material:** Supplementary Material associated with this publication is available upon request.

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## **Chapter 6: Modelling the effect of context-specific greenhouse gas and nitrogen emission mitigation options in key European dairy farming systems**

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## Abstract

European dairy production systems (DPS) face stricter and increasingly binding environmental protection requirements. Understanding the impacts associated with DPS is a crucial step for identifying and implementing context-specific mitigation strategies. In this context, few studies have modelled the effect of tailored emission mitigation options on relevant DPS across Europe. Here, we assess the single and combined effect of six emission mitigation practices on selected case studies for dairy production located in key European regions through the Sustainable and Integrated Management System for Dairy Production (SIMS<sub>DAIRY</sub>) model. The results showed how reducing the crude protein content of the purchased fraction of the diet was an adequate mitigation strategy to reduce the greenhouse gas (GHG<sub>int</sub>) and the nitrogen emission intensity (N<sub>int</sub>) in all systems. Furthermore, implementing an anaerobic digestion plant reduced the GHG<sub>int</sub> in all tested DPS while increasing the N<sub>int</sub> only from the intensive Mediterranean case study. As for the productivity increase, contrasting effects were observed amongst the DPS modelled when the supply of purchased feed was higher. Likewise, shallow slurry injection effectively reduced the N<sub>int</sub> at the field level while marginally increasing the GHG<sub>int</sub> in the Mediterranean DPS. When substituting urea as mineral fertilizer, a greater mitigation potential of the GHG<sub>int</sub> and the N<sub>int</sub> was observed in the Atlantic semi-extensive DPS than in the intensive Mediterranean system. Regarding rigid slurry covers, these effectively reduced the storage-related N<sub>int</sub> while showing a minor effect on total GHG<sub>int</sub>. In addition, our results provided novel evidence regarding the advantages of cumulative implementation of adapted mitigation options to offset the negative trade-offs of single-option applications. Through this study, we contribute to a better understanding of the effect of emission mitigation options across DPS in Europe, thus facilitating the adoption of tailored and context-specific emission reduction strategies.

**Key words:** Sustainability, mitigation, modelling, emissions and dairy.

## 1. Introduction

Dairy cattle production systems (DPS) are a strategic food production sector for the socioeconomic development of Europe (Bórawski et al. 2020). They provide strong elements of identity and cultural heritage by preserving traditions, landscapes and biodiversity (Sturaro et al. 2013). In addition, unlike other animal categories, ruminants are able to transform fibrous biomass, inedible for humans or monogastric animals, into high-quality nutritionally concentrated products, thereby contributing to global food security (Ertl et al. 2015; Feil et al. 2020). Likewise, in addition to the provision of feed for the DPS, the maintenance of grasslands is presented as a way to increase carbon stocks, thus contributing to the mitigation of agricultural greenhouse gas emissions (Whitehead 2020). However, the increasing demand for milk and dairy products, together with a shift towards production intensification, heavily affects the environmental impact, social perception, and economic performance of the sector (Salou et al. 2017; Styles et al. 2018). In this complex and challenging scenario, it is essential that adapted approaches are taken to ensure the future feasibility and sustainability of DPS (Díaz de Otálora et al. 2021).

Greenhouse gas (GHG) emissions and nitrogen (N) losses from livestock production represent significant environmental and health risks. At the global scale, 14.5% of anthropogenic GHG emissions come from the livestock sector (Gerber et al. 2013), of which 20% are directly associated with DPS (Tricarico et al. 2020). On-farm methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) contribute the most to non-carbon dioxide emissions from DPS (UNFCCC 2023). For the year 2020, enteric fermentation and manure management CH<sub>4</sub> emissions accounted for 2738 kilotons (kt), whereas those associated with N<sub>2</sub>O emissions (fields and manure management) reached a value of 2.57 kt (FAO 2023). Furthermore, reactive N losses in the form of ammonia (NH<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), and N<sub>2</sub>O associated with manure management (fields and storage) and fertilizers are key drivers of the environmental impact of DPS (Leip et al. 2015). In this sense, at the European level, NH<sub>3</sub> and NO<sub>x</sub> emissions greatly contribute to the total particulate matter emissions (PM<sub>2.5</sub>) (Wyer et al., 2022). Furthermore, nitrate leaching (NO<sub>3</sub><sup>-</sup>) into waterways could potentially increase the water toxicity for animal and human consumption (Doole 2012). However, the sources and magnitude of these emissions are highly dependent on management practices. Different feed compositions, manure management practices, or fertilization schemes condition the emissions associated DPS (Christie et al. 2011; Wattiaux et al. 2019). Similarly, GHG and N emissions are sensible to the existing pedoclimatic conditions (i.e., temperature, soil type, precipitation, etc.). Clear examples of this effect is the direct correlation between CH<sub>4</sub>

emission from manure and temperature (Baldé et al. 2016), or the link between some soil texture and GHG and N emission from fertilizer application (Shakoor et al. 2021). In this context, improved animal efficiency, better slurry storage and application practices, and the use of alternative mineral fertilizers have been described as effective measures to reduce GHG and N emissions of DPS (Aguirre-Villegas et al. 2019; Narthey et al. 2021; Arndt et al. 2022).

To date, the effect of individual mitigation measures on single farms and specific emission sources has been widely explored in the literature. Previous studies have pointed out the positive effect of diet-oriented mitigation options on CH<sub>4</sub> and NH<sub>3</sub> emissions (Ouatahar et al. 2021). Substantial reductions in enteric CH<sub>4</sub> have been reported by increasing the level of concentrates in the diet and modulating the forage-to-concentrate (F:C) ratio (Martin et al. 2010; Congio et al. 2021). In addition, modulating dietary protein content has been shown to limit N losses from DPS (Sajeev et al. 2018b). As for emissions derived from manure management, DPS represent an important source of GHG and N losses (Vangeli et al. 2022). To this end, improved manure management and slurry application techniques contribute to reducing these emissions (Owen and Silver 2015; Petersen 2018). Moreover, high-efficiency covers and anaerobic digestion (AD) plants significantly reduce NH<sub>3</sub>, CO<sub>2</sub>, and CH<sub>4</sub> emissions, and for the latter, generate energy from alternative sources (Clemens et al. 2006; Burg et al. 2018; Kupper et al. 2020). However, scale and contextual limitations in existing studies do not allow for a comprehensive assessment of different mitigation measures on relevant DPS typologies. Thus, it is necessary to better evaluate the single and combined effect of adapted mitigation measures on key European DPS, facilitating the application of adapted policies for reduced environmental impact. In this context, the combination of measures seems to be an appropriate solution to minimize the negative effects of their individual application by promoting synergies and positive interactions (Prudhomme et al. 2020).

Amongst the wide range of available approaches and methods, whole-farm models are presented as valuable tools to analyze the effects of mitigation options on DPS sustainability (Crosson et al. 2011). These models consider individual farm processes in a systemic manner capturing the trade-offs between farm components (i.e., soil, crops, feed, animals and manure) and assessing the interactions with GHG and air pollutants (Schils et al. 2007a). In this context, selecting the most appropriate modelling tool essential for obtaining meaningful results (Díaz de Otálora et al. 2021). The Sustainable and Integrated Management Systems for Dairy Production (SIMS<sub>DAIRY</sub>) integrates the major components of a dairy farm into a modelling framework with a system-based approach (Del Prado et al. 2011). In this way, interactions between farm management, climatic

conditions, and environmental characteristics are evaluated, and their effects on GHG and N emissions are simulated (Del Prado and Scholefield 2008; Del Prado et al. 2010, 2013b).

Given the diversity of DPS across Europe, the effectiveness and applicability of mitigation options are subject to major uncertainty (Sommer et al. 2009). Different levels of specialization, structural characteristics, and production contexts can classify DPS into multiple typologies, and largely determine their emission performances and mitigation potentials (Gonzalez-Mejia et al. 2018; Díaz de Otálora et al. 2022). In this context, there is a lack of knowledge about the effect of different emission reduction options on a diversity of DPS. Since the adoption of approaches considering the particular attributes of the different farms is a much-needed prerequisite for the successful reduction of the emission on DPS, this study aims to assess the effect of selected and context-specific mitigation options on a wide range of GHG and N emissions of six key DPS across Europe through the SIMS<sub>DAIRY</sub> model. Furthermore, the combined effects of GHG and N mitigation measures at the whole-farm level are assessed, thus paving the way for better and more adapted decision-making.

## **2. Material and methods**

### **2.1. DPS description**

Data for the 2020 accounting year from six case study farms located across Europe (Germany, Poland, Italy, Norway, and Ireland) was used for this study. All the DPS assessed specialized in milk production, having more than two-thirds of their economic output came from dairy farming (EUROSTAT 2015). The selected case studies represented different typologies of DPS based on their production systems, intensity, productivity, management practices, structural characteristics, and socioeconomic attributes (Díaz de Otálora et al. 2022). The required information for the modelling exercise and their characterization (i.e., herd management and production, manure and fertilization management, production, etc.) was collected through interviews with the farmers in 2021 and 2022. The monthly meteorological information (average temperature, rainfall, wind speed, and rain days) was extracted from the closest weather station to the farms for the assessed period (2020). Key attributes of the different DPS analyzed are presented in Table 1.

**Table 1:** Key features of the dairy production systems modelled. WC<sub>i</sub> Western European conventional intensive system; WO<sub>s</sub> Western European organic semi-extensive system; EC<sub>s</sub> Central-Eastern European conventional semi-extensive system; MC<sub>i</sub> Mediterranean conventional intensive system; NC<sub>s</sub> Northern European conventional semi-extensive system; AC<sub>s</sub> Atlantic conventional semi-extensive system; °C degrees centigrade; mm millimetres; FPCM fat and protein corrected milk; UAA utilized agricultural area; CAN calcium ammonium nitrate; U urea; AN ammonium nitrate. <sup>a</sup> standardized to 4% fat and 3.3% protein per kilogram (IDF 2015); <sup>b</sup>50% Holstein, 40% Montbéliarde, and 10% Polish red; <sup>c</sup> 50% Holstein and 50% Jersey; <sup>d</sup>20% of the diet composed by self-produced cereal mix (no concentrates bought); <sup>e</sup> more than one typology of mineral fertilizer is applied

	Units	WC <sub>i</sub>	WO <sub>s</sub>	EC <sub>s</sub>	MC <sub>i</sub>	NC <sub>s</sub>	AC <sub>s</sub>
Location	-	Germany	Germany	Poland	Italy	Norway	Ireland
Production system	-	Conventional	Organic	Conventional	Conventional	Conventional	Conventional
Degree of intensification	-	Intensive	Semi-extensive	Semi-extensive	Intensive	Semi-extensive	Semi-extensive
Average monthly temperature	°C	12	11	7	14	7	10
Average monthly precipitation	mm	72	50	63	66	84	123
Soil texture	-	Sand	Sandy loam	Clay loam	Sandy loam	Clay	Loam
Dairy animals	Animals	138	240	50	565	55	185
Young animals	Animals	62	124	61	575	62	115
Main cow breed	Name	Holstein	Holstein	Crossbreed <sup>b</sup>	Holstein	Norwegian red	Crossbreed <sup>c</sup>
Milk production	kg FPCM <sup>a</sup> animal <sup>-1</sup> year <sup>-1</sup>	11171	7709	8880	10766	7848	5511
Milk yield	kg animal <sup>-1</sup> day <sup>-1</sup>	30.7	21.2	24.4	29.6	21.5	15.1
Forage-to-concentrate	Ratio	70:30	80:20 <sup>d</sup>	80:20	50:50	55:45	85:15
Crude protein in purchased feed	%	28	11	23	13	18	14
Silage type	-	Grass/Maize	Grass/Maize	Grass/Maize	Grass/Maize	Grass	Grass
Farm area (UAA)	ha	71	495	80	260	87	87
Main use of UAA	-	Maize	Grass	Grass	Maize	Grass	Grass
Grazing time (adult)	Days	0	215	164	0	139	266
Slurry storage cover	Type	Crusted	Crusted	Rigid	Crusted	Rigid	Crusted
Slurry application technique	Type	Shallow injection	Shallow injection	Broadcast	Broadcast	Broadcast	Shallow injection
Main mineral fertilizer	Type	CAN <sup>e</sup>	-	U <sup>e</sup>	U	AN <sup>e</sup>	U

As for the pedoclimatic characteristics, the Western European conventional intensive DPS ( $WC_i$ ) featured a sandy soil and a temperate humid climate, while the Western European organic semi-extensive DPS ( $WO_s$ ) presented a sandy loam soil with a cold humid climate. Likewise, the Central-Eastern European conventional semi-extensive DPS ( $EC_s$ ) exhibited a cold humid climate with a clay loam soil texture. The Atlantic conventional semi-extensive ( $AC_s$ ) had the same climate as  $WC_i$  but presented a loam soil texture. As for the Mediterranean European conventional intensive DPS ( $MC_i$ ), a temperate humid climate and sandy loam soil were noted. Lastly, the Northern European conventional semi-extensive DPS ( $NC_s$ ) presented a cold, humid climate and a clay soil texture.

The size of the farms in terms of the number of animals varied from large farms in Southern Europe ( $MC_i$ ) to small farms in Central-Eastern Europe ( $EC_s$ ). However, the number of animals was not directly correlated with the size of the farm in terms of utilized agricultural area (UAA), resulting in a lower stocking rate on farms with a larger area (i.e.,  $WO_s$ ). In addition, diet played a fundamental role in determining the productivity of the analyzed DPS. Higher productivity was associated with intensive systems characterized by a more significant presence of concentrates (lower forage-to-concentrate ratio), whole plant maize in the diet, and the absence of grazing. This was the case for  $WC_i$ , with 30.7 kg milk cow<sup>-1</sup> day<sup>-1</sup>, and  $MC_i$ , with 29.6 kg milk cow<sup>-1</sup> day<sup>-1</sup>. In contrast, semi-extensive systems with greater forage in the diet (mainly grass, grass silage or maize silage) and more grazing days present lower milk yields. This is especially notable in  $AC_s$ , where production was 15.1 kg milk cow<sup>-1</sup> day<sup>-1</sup>, or in  $WO_s$  and  $NC_s$ , where productivity reached 21.2 and 21.5 kg milk cow<sup>-1</sup> day<sup>-1</sup>.

As for manure management (production, storage, and application), the evaluated farms showed significant differences in the systems present and technologies applied. All DPS, except for  $EC_s$ , were characterized by the predominance of liquid slurry as a manure management system (on average, 77% slurry compared to 23% solid manure). In the case of  $EC_s$ , 50% of the manure was managed as solid (farmyard manure). Regarding slurry storage, a great diversity of technologies were observed. In this sense, open tanks with crust were the predominant typology ( $WC_i$ ,  $WO_s$ ,  $MC_i$ , and  $AC_s$ ), followed by rigid covers ( $NC_s$  and  $EC_s$ ). In all DPS, the slurry was applied as organic fertilizer using a shallow injection ( $WC_i$ ,  $WO_s$ , and  $AC_s$ ) or broadcast ( $EC_s$ ,  $MC_i$ , and  $NC_s$ ).

Finally, as for mineral fertilization, three were the predominant typologies observed: calcium ammonium nitrate (CAN), ammonium nitrate (AN), and urea. Mineral fertilizer was applied in all the DPS analyzed, except in the system with organic production ( $WO_s$ ). In the case of  $MC_i$

and AC<sub>s</sub>, only urea was applied as mineral fertilizer in doses of 96 and 43 kg N ha<sup>-1</sup>. In EC<sub>s</sub> and NC<sub>s</sub>, a combination of AN and urea was applied, reaching a total dose of mineral N of 43 and 109 kg N ha<sup>-1</sup>. Finally, CAN and urea was applied in WC<sub>i</sub>, with a total farm-level dose of mineral fertilizer of 85 kg N ha<sup>-1</sup>.

## 2.2. Modelling environmental impacts

SIMS<sub>DAIRY</sub> is one of the existing whole-farm models specifically developed to assess GHG and N emissions from DPS (Schils et al. 2007b; Del Prado et al. 2013a). A detailed description of the main characteristics and underlying principles of the model used for this manuscript (including the original and modified version used in this study) are described in Del Prado et al. (2011b) and the Supplementary Material 4. SIMS<sub>DAIRY</sub> has proved its appropriateness for assessing synergies and trade-offs associated with different farming management options since it showcases the effect of various management strategies on N losses and GHG emissions from different sources (Del Prado et al. 2010).

SIMS<sub>DAIRY</sub> integrates the significant components of a dairy farm (i.e., animals, manure, fields, off-farm emissions, etc.) into a modelling framework using a system-based approach. Furthermore, the modular construction of SIMS<sub>DAIRY</sub> allows to perform calculations at different farm levels or subsystems either using already existing models (i.e., MANNER (Chambers et al. 1999) and NGAUGE (Brown et al. 2005)) or specific module developments. In this way, N flows and GHG emissions for a given combination of management strategies, soil types and farm characteristics (i.e., manure storage and application) are simulated.

As for the model calculations, these are represented by the following sequence (Figure 9 of Supplementary Material 4). First, the dry matter (DM) yield, N per ha and the crude protein (CP) content of forage crops in the fields is calculated based on the monthly-based NGAUGE model results that include all N inputs to the fields except for those coming from stored manure (stored manure is calculated as an internal flow in subsequent steps). Second, animal energy requirements are estimated using as input the herd management characteristics and the previously estimated nutritional values (i.e., CP) from on-farm forage. Additionally, manure emissions and a first estimation of manure characteristics (i.e., total N and ammonium N) and total volume applied to the field are also calculated based on the first animal and field calculations. At this stage, on-farm forage surface is estimated (requirements of initial on-farm forage DM are met with DM per ha yields from the different field types). Therefore, as third step, there is a subsequent update of DM and N yield per ha, as well as CP content of forage considering the

fertilizing effect of applied manure too. Fourth, another iteration of the model updates the previously estimated animal energy requirements using the updated on-farm forage characteristics. In this step, CH<sub>4</sub> from enteric fermentation, manure volatile solids and manure CH<sub>4</sub>, and N losses are calculated. SIMS<sub>DAIRY</sub> will repeat these iterations until a steady state is reached (i.e., until the forage hectares of each field type do not significantly change from one iteration to the subsequent one).

As for emission calculations, enteric CH<sub>4</sub> is estimated following a Tier 2 approach from the latest Intergovernmental Panel on Climate Change (IPCC) refinement to the Guidelines (Gavrilova et al. 2019). These emissions are calculated from the gross energy (GE) intake and the methane emission factor ( $Y_m$ ) as a function of feed quality and level of feed intensification. Animal performance and diet data are used to estimate feed intake according to animal needs. Likewise, CH<sub>4</sub> emission from manure are calculated using the approach from the IPCC 2019 Guidelines refinement (Gavrilova et al. 2019). In this case, volatile solid content is calculated on a monthly basis using emission factors (EF) or, in the case of slurry storage, following the approach provided in the spreadsheet model for slurry emissions from the IPCC (MCF Calculations Example Spreadsheet) (Gavrilova et al. 2019). Furthermore, excreted N by the animals is estimated by subtracting N in milk and net body change from the N ingested by each type of animal (i.e., grazing or housed). In this case, urine and dung losses are divided following the equations derived from existing trials where urine and dung N is expressed as a function of N and DM intake (Reed et al. 2015).

Reactive nitrogen losses (NH<sub>3</sub>, N<sub>2</sub>O, NO<sub>3</sub><sup>-</sup> and NO<sub>x</sub>) are divided in two groups: (i) manure (housing, yards and storage), and (ii) fields and crops (fields and silage). The manure N losses and flows are simulated following the principles of a mass-balance approach (Webb and Misselbrook 2004). Reactive N losses are calculated from the pool of total ammoniacal nitrogen (TAN) in manure according to different EF for different manure management stages. As for housing emissions, SIMS<sub>DAIRY</sub> follows the approach and EF reported by the European Monitoring and Evaluation Programme (EMEP) (European Environmental Agency 2019). For this, two initial separate housing phases (yards and housing) are considered. After subtracting N losses generated during housing from the initial TAN content in manure, N losses from storage are predicted as a percentage of the remaining TAN content using EF for different storage systems (Del Prado et al. 2011).

As for the field and crop N losses, these are modelled through a semi-mechanistic approach, whereby pedoclimatic characteristics determine the amount of soil inorganic N that is denitrified,



nitrified or lost as leaching. In this case, the model NGAUGE was applied following the iterations described above. Parameters sensitive to soil moisture and air temperature have been adjusted for Europe's diversity. Furthermore, SIMS<sub>DAIRY</sub> estimates the amount of nitrogen lost (NH<sub>3</sub> and NO<sub>x</sub>) during silage conservation. The model considers five qualitative classes of silage management quality (from very good to very poor) associated with a fixed N loss (Bastiman and Altman 1985).

Furthermore, Supplementary Material 4 provides a sensitivity analysis of the original version of the SIMS<sub>DAIRY</sub> modelling framework. In this analysis, the influence of selected numerical and categorical input variable values (i.e., days in housing, herd size, milk production, protein/fat content, dietary neutral detergent fiber content, manure application, soil texture, slurry application method, etc.) on output variables (i.e., N losses, surface area, etc.) was tested. According to the results, SIMS<sub>DAIRY</sub> was sensitive to relevant numerical and categorical variable changes.

Total GHG and N emission intensities (GHG<sub>int</sub> and N<sub>int</sub>) were calculated through the following equation (Eq.1):

$$Em_{int} = \sum Em_{individual} \quad (1)$$

where  $Em_{int}$  represents the GHG<sub>int</sub> (expressed in kg CO<sub>2eq</sub> kg milk<sup>-1</sup>) or N<sub>int</sub> (expressed in g N kg milk<sup>-1</sup>).

In the case of the GHG<sub>int</sub>,  $\sum Em_{individual}$  considers all the GHG emission intensities under study (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O). CH<sub>4</sub> and N<sub>2</sub>O emissions were converted to CO<sub>2eq</sub> using the 100-year Global Warming Potential (GWP-100) values of 27.2 (non-fossil fuel CH<sub>4</sub>) and 273 (N<sub>2</sub>O) according to the latest Sixth Assessment Report (AR6) from the IPCC (Forster et al. 2021). As for the N<sub>int</sub>,  $\sum Em_{individual}$  represents the sum of all the emission intensities from the reactive N losses assessed (NH<sub>3</sub>, NO<sub>3</sub><sup>-</sup>, N<sub>2</sub>O and NO<sub>x</sub>). These emissions were normalized based on their nitrogen content (NO<sub>x</sub>-N, N<sub>2</sub>O-N, NH<sub>3</sub>-N and NO<sub>3</sub><sup>-</sup>-N).

### 2.3. Mitigation measures

The modelled emission reduction options were selected based on two criteria: i) mitigation strategies had to be implemented by modifying the user inputs required by SIMS<sub>DAIRY</sub>, and ii) mitigation options should cover different management aspects of DPS (fields, manure, diet, animals, etc.). As a result, six mitigation options were identified and classified in two categories according to their scope: i) diet management and ii) slurry management and fertilizer application.

### **2.3.1. Diet management**

An increase in the productive performance associated with a greater fraction of purchased feed (i.e., concentrate) (PI) was simulated. This measure has previously proven effective in reducing enteric CH<sub>4</sub> emissions (Arndt et al. 2022), and was especially relevant in DPS typologies with high forage supply and low productivity. However, the optimal ratio of forage to concentrate in lactating dairy cows is commonly discussed in the literature. A forage-to-concentrate ratio (F:C) of 70:30 is considered a high-forage formulation, while a ratio of 30:70 is considered a low-forage diet (Jaakamo et al. 2019). In this sense, a F:C ratio of 60:40 is commonly seen as a good compromise concerning milk yield and emissions (Mertens 2009; Aguerre et al. 2011). To this end, in conventional dairy production systems with a ratio above 70:30 their forage ratio in the diet was reduced to 60:40. As an organic DPS that originally did not present any purchased feed, WO<sub>s</sub> was excluded from this mitigation strategy. Furthermore, the reduction of the forage supply has been related to increased productivity due to lower fibre content of the diet (Ben Meir et al. 2021). Previous studies increasing the concentrate in the diet have observed an increase in production close to 15% (13.65%) (Mckay et al. 2019). As an approximation to the previously observed results, a 15% increase was applied in both DPS.

Second, the crude protein (CP) content of the purchased feed was reduced to minimize N excretion in the farms. This measure was proven to have a mitigating effect on NH<sub>3</sub> emissions (Hristov et al. 2011), and was particularly suitable for DPS where the CP content of the purchased fraction of the diet was exceptionally high. While WO<sub>s</sub>, MC<sub>i</sub>, and AC<sub>s</sub> had values between 12 and 14%, higher values observed in WC<sub>i</sub> (28%), EC<sub>s</sub> (23%) and NC<sub>s</sub> (18%). In this line, previous studies have demonstrated that reducing CP levels to around 14% in dairy cow diets increases the efficiency and reduces N excretion while not affecting the productive performance of the animals (Sinclair et al. 2014; Hynes et al. 2016). In consequence, the CP content of the purchased fraction of the diet was reduced to 14% in WC<sub>i</sub>, EC<sub>s</sub> and NC<sub>s</sub>.

### **2.3.2. Slurry management and fertilizer application**

Regarding slurry management and fertilizer application, four mitigation measures were modelled. First, the effect of high-efficiency covers on slurry storage (HES<sub>c</sub>) was evaluated as a mitigation option for reducing N losses during the storage phase (Oenema et al. 2007). The impact of rigid covers was modelled in DPS that initially presented with open or slatted storage (with or without a crust). This was the case of WC<sub>i</sub>, WO<sub>s</sub>, MC<sub>i</sub>, and AC<sub>s</sub>. Second, concerning the slurry application, several authors highlighted the mitigation potential of high-efficiency shallow injection (HES<sub>a</sub>) techniques compared to broadcast to reduce NH<sub>3</sub> emissions (Duncan et al.

2017). To this end, shallow injection was implemented in DPS where slurry was applied using broadcast (i.e., EC<sub>s</sub>, MC<sub>i</sub>, and NC<sub>s</sub>).

Urea is one of the most widely used nitrogen sources at the same time that is associated with significantly NH<sub>3</sub> emissions than other mineral fertilizers (i.e., ammonium nitrate(AN)) (Del Moro et al. 2017). Therefore, substituting urea with alternative fertilizers has been reported as an effective mitigation measure to reduce NH<sub>3</sub> emissions (Ti et al. 2019). In this case, the substitution of urea by AN was evaluated in those DPS where only urea was applied (keeping the originally reported rate of application). Likewise, it was ensured that none of the DPS where this mitigation option was applied had sandy soil texture, which is commonly associated with higher nitrate leaching (Witheetrirong et al. 2011). Consequently, MC<sub>i</sub> and AC<sub>s</sub> were selected for this mitigation strategy.

Lastly, the effect of anaerobic digestion (AD) was modelled. The proposed AD plant only considers the slurry produced in the different DPS as substrate. Although AD plants commonly rely on crop residues, energy crops (i.e., maize), and other organic residues as substrates, in this manuscript, the theoretical effect of slurry-based AD on the GHG and N losses was modelled. The implementation of AD it is largely limited by the slurry availability (Scott and Blanchard 2021). Therefore, we assumed that DPS with at least 100 livestock units (LU) and cattle staying less than two-thirds of the year at pasture qualified for this mitigation option (i.e., WC<sub>i</sub>, WO<sub>s</sub> and MC<sub>i</sub>), as an appropriate flow of slurry is necessary to ensure the economic and technical viability of the digester (Pellerin et al. 2013; Höglund-Isaksson et al. 2016). In order to simulate the C and N transformations associated with manure processed through AD, the SIMS<sub>WASTE</sub> model was applied (Pardo et al. 2017). Flow (on a yearly basis) and basic chemical composition of manure (i.e., volatile solids, N, and TAN) were detailed as primary inputs. In addition, parameters describing operational conditions were modelled. A mesophilic temperature regime was assumed in the digester, in a covered digestion tank with residual biogas collection. The amount and composition of biogas and digestate (i.e., TAN content) were estimated as outputs of the model, as well as energy produced and gaseous emissions associated with digester leakages and biogas combustion. Avoided emissions of manure processed through AD were calculated according to IPCC guidelines (Gavrilova et al. 2019), considering slurry storage as the default manure management system. Avoided emissions of biogas energy production were calculated assuming that biogas displaces electricity production from natural gas, according to an emission factor of 0.47 tCO<sub>2eq</sub> megawatts<sup>-1</sup> (Swiss Center for Life Cycle Inventories 2016). In addition, slurry derived from AD (digestate) was subsequently applied as organic fertilizer in a similar manner

to the baseline scenario with untreated manure but considering the new characteristics regarding total and inorganic N content.

### 3. Results and discussion

#### 3.1. Baseline GHG and N emission intensity

An average  $\text{GHG}_{\text{int}}$  of  $1.19 \pm 0.387 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$  was obtained. As shown in Table 2, the highest values were observed in the Mediterranean conventional intensive DPS ( $\text{MC}_i$ ) ( $1.75 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ ). The Eastern-Central European conventional semi-extensive DPS ( $\text{EC}_s$ ) had a  $\text{GHG}_{\text{int}}$  of  $1.42 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ , followed by the Northern conventional semi-extensive DPS ( $\text{NC}_s$ ) with  $1.40 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ . The Atlantic conventional semi-extensive DPS ( $\text{AC}_s$ ) accounted for a  $\text{GHG}_{\text{int}}$  of  $0.89 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ , while the Western European organic semi-extensive DPS ( $\text{WO}_s$ ) obtained a  $\text{GHG}_{\text{int}}$  of  $0.85 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ . Finally, the lowest  $\text{GHG}_{\text{int}}$  was observed in the Western European conventional intensive DPS ( $\text{WC}_i$ ) with  $0.82 \text{ kgCO}_{2\text{eq}} \text{ kg milk}^{-1}$ .

When comparing the results obtained with those reported in the literature, baseline  $\text{GHG}_{\text{int}}$  for both German DPS aligns with previously obtained results ( $0.8\text{-}1.8 \text{ kg CO}_{2\text{eq}} \text{ kg milk}^{-1}$ ) (Zehetmeier et al. 2020). As for  $\text{MC}_i$ , previous studies for Italian DPS with similar milk production, showed values between  $1.3$  and  $1.6 \text{ kg CO}_{2\text{eq}}$  per unit of product (Lovarelli et al. 2019). For this context, the obtained results align with previous authors findings (given the different methodologies used). The results obtained in the  $\text{NC}_s$  were similar that those observed by previous authors who, in comparable productive and geographical contexts, observed GHG emissions ranging between  $1.2$  and  $1.6 \text{ kg CO}_{2\text{eq}} \text{ kg milk}^{-1}$  (Mittenzwei 2020). Lastly, concerning  $\text{AC}_s$ , farms with comparable productions ( $5500 \text{ kg FPCM animal}^{-1} \text{ year}^{-1}$ ) obtained a value of total GHG emissions close to  $1 \text{ kg CO}_{2\text{eq}} \text{ kg milk}^{-1}$  (O'Brien et al. 2015), in line with the results obtained for this study.

On average, enteric and manure  $\text{CH}_4$  and  $\text{CO}_2$  from feed purchases constituted 67% of the  $\text{GHG}_{\text{int}}$ . Enteric  $\text{CH}_4$  emissions were the largest source of GHG in all DPS, representing 40% of the average  $\text{GHG}_{\text{int}}$ . However, differences were observed across the analyzed DPS. For instance, the percentage of  $\text{GHG}_{\text{int}}$  associated with enteric  $\text{CH}_4$  in intensive DPS ( $\text{WC}_i$ , and  $\text{MC}_i$ ) was lower than that obtained for semi-extensive systems ( $\text{WO}_s$ ,  $\text{EC}_s$ ,  $\text{NC}_s$ , and  $\text{AC}_s$ )  $34 \pm 8.4\%$  vs.  $43 \pm 14.9\%$ . These lower values were associated with the feeding strategy, predominantly based on concentrates and forage such as green maize, whose higher digestibility reduces fermentation time and enteric  $\text{CH}_4$  emissions (Hassanat et al. 2013; Lettat et al. 2013). Conversely, intensive

systems showed a higher share of manure CH<sub>4</sub> emissions over the total GHG<sub>int</sub> than those observed for semi-extensive DPS (18±2.1% vs. 10±3.4%). As acknowledged by previous authors, intensification is associated with larger direct manure-related emissions (Petersen et al. 2013). A greater manure volume, derived partly from the lack of grazing, could increase emissions of this gas (Im et al. 2020). Additionally, while emissions associated with feed purchase represented 11±8.5% of GHG<sub>int</sub> in semi-extensive DPS, higher values were reached in the intensive systems (22±2.4%). This could be due to the fact that intensive DPS are characterized by a higher reliance on off-farm feed inputs (Reinsch et al. 2021) which are commonly associated with significant off-farm GHG emissions (Battini et al. 2016). Lastly, as noted by previous authors, excretion during grasslands substantially contribute to the N<sub>2</sub>O emissions (Soares et al. 2023). This is confirmed by our results that showed higher N<sub>2</sub>O emissions (direct and indirect) from the fields in semi-extensive (13±9.6%) than intensive (12±11.8%) DPS.

Concerning the N<sub>int</sub>, an average value of 8.4±3.09 g N kg milk<sup>-1</sup> was obtained. In this context, previously published modelling results at the European scale indicated that total N emissions per unit of dairy product ranged from 10 to 50 g N kg<sup>-1</sup> (Leip et al. 2014). As for the individual assessment, the highest values were observed in the Mediterranean intensive conventional case study (MC<sub>i</sub>) and the Northern conventional semi-extensive (NC<sub>s</sub>) DPS with 12.1 g N kg milk<sup>-1</sup> each. The Western European conventional intensive system (WC<sub>i</sub>) accounted for 8.3 g N kg milk<sup>-1</sup>, while the Eastern-Central conventional semi-extensive DPS (EC<sub>s</sub>) presented 7.3 g N kg milk<sup>-1</sup>. Lastly, the Western European semi-extensive organic (WO<sub>s</sub>) systems accounted for 5.5 g N kg milk<sup>-1</sup> and the Atlantic European semi-extensive conventional (AC<sub>s</sub>) had a value of 5.0 g N kg milk<sup>-1</sup>.

The breakdown of the N losses showed that, on average, 57% of the N<sub>int</sub> was associated with NH<sub>3</sub> emissions. To a lesser extent, NO<sub>3</sub><sup>-</sup> represented 33% of the N<sub>int</sub>, while NO<sub>x</sub> and N<sub>2</sub>O emissions accounted for 6 and 4%, respectively. The fields were the largest source of N losses, averaging 61% of the N<sub>int</sub>. Higher values were shown in semi-extensive systems (WO<sub>s</sub>, EC<sub>s</sub>, NC<sub>s</sub>, and AC<sub>s</sub>) than in intensive DPS (WC<sub>i</sub> and MC<sub>i</sub>), with values ranging between 62±5.7% and 60±14.9%. Although fertilizers were applied in both semi-extensive and intensive DPS, a higher deposition of excreted N in fields was noted in semi-extensive DPS. According to the literature, this is one of the key factors causing higher N emissions for this DPS typology (Gourley et al. 2012). As for the combined N losses during housing and yards, our results showed higher emissions for intensive DPS than in semi-extensive DPS (21±8.9% versus 17±2.8%). In contrast, N emissions from storage were similar in both in semi-extensive (7±4.0%) and in intensive (6±1.3%) DPS.

Emissions regarding silage making could be a concern DPS based on their location and production system. In this context, as described by previous authors, intensive farms are more inclined to use high-quality silage in addition to concentrate (Gallo et al. 2022). However, in our case, similar silage emissions were observed in the semi-extensive than in the intensive DPS.

**Table 2:** Greenhouse gas (GHG) and nitrogen (N) emission intensity for the modelled baseline dairy production systems. WC<sub>i</sub> Western European conventional intensive system; WO<sub>s</sub> Western European organic semi-extensive system; EC<sub>s</sub> Central-Eastern European conventional semi-extensive system; MC<sub>i</sub> Mediterranean conventional intensive system; NC<sub>s</sub> Northern European conventional semi-extensive system; AC<sub>s</sub> Atlantic conventional semi-extensive system; CH<sub>4</sub> methane; N<sub>2</sub>O nitrous oxide; CO<sub>2</sub> carbon dioxide; NH<sub>3</sub> ammonia; NO<sub>x</sub> nitrogen oxide; NO<sub>3</sub><sup>-</sup> nitrate.

	WC <sub>i</sub>	WO <sub>s</sub>	EC <sub>s</sub>	MC <sub>i</sub>	NC <sub>s</sub>	AC <sub>s</sub>
GHG emission intensity						
Enteric CH <sub>4</sub>	0.325	0.433	0.413	0.482	0.453	0.534
Manure CH <sub>4</sub>	0.159	0.081	0.206	0.286	0.093	0.077
Direct manure N <sub>2</sub> O	0.011	0.007	0.024	0.013	0.009	0.007
Indirect manure N <sub>2</sub> O	0.017	0.007	0.015	0.014	0.015	0.006
Direct field N <sub>2</sub> O	0.007	0.029	0.365	0.311	0.122	0.057
Indirect field N <sub>2</sub> O	0.021	0.018	0.018	0.040	0.041	0.018
Feed purchase (CO <sub>2</sub> )	0.170	0	0.152	0.420	0.281	0.129
Energy use (CO <sub>2</sub> )	0.109	0.273	0.211	0.172	0.351	0.054
Fertilizer purchase (CO <sub>2</sub> )	0.006	0	0.013	0.007	0.040	0.006
Total GHG emission intensity	0.824	0.848	1.417	1.747	1.404	0.888
N emission intensity						
Ammonia (NH <sub>3</sub> )	4.155	3.128	5.318	5.120	6.339	3.276
Nitrate (NO <sub>3</sub> <sup>-</sup> )	3.547	1.905	0.673	5.747	4.801	1.377
Nitrous oxide (N <sub>2</sub> O)	0.042	0.083	0.907	0.756	0.306	0.149
Nitrogen oxide (NO <sub>x</sub> )	0.536	0.431	0.369	0.451	0.650	0.274
Total nitrogen emission intensity	8.279	5.547	7.268	12.074	12.095	5.075
N emission sources						
Yards	0.764	0.238	0.423	0.607	0.915	0.317
Housing	1.517	0.567	1.086	1.195	1.071	0.463
Storage	0.566	0.303	0.920	0.602	0.436	0.278
Fields	4.132	3.430	3.921	8.573	8.036	3.329
Silage	1.299	1.009	0.919	1.097	1.637	0.689

### 3.2. Mitigated modelling

Main variations with respect to the baseline modelling for each individual gas (i.e., CH<sub>4</sub>, N<sub>2</sub>O, CO<sub>2</sub>, NH<sub>3</sub>, NO<sub>3</sub><sup>-</sup>, and NO<sub>x</sub>) were detailed. Complete results could be found in the Supplementary Material 1 (expressed in %) and Supplementary Material 2 (expressed in absolute values).

#### 3.2.1. Diet management

The increase in the productive performance (PI) decreased the N<sub>int</sub> in AC<sub>s</sub> by 0.65 (-13%) and increased by 0.18 (3%) g N kg milk<sup>-1</sup> the one of the EC<sub>s</sub>. In the same line, this mitigation option showed mixed effects on the overall GHG<sub>int</sub> showing a reduction of 0.06 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-4%) in EC<sub>s</sub> and an increase of 0.04 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (+5%) in AC<sub>s</sub>. Both enteric and manure CH<sub>4</sub> emissions intensity were substantially mitigated in both DPS, showing reductions of 0.05 (-11%) and 0.04 (-18%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in the EC<sub>s</sub>, and 0.06 (-12%) and 0.01 (-17%) in the AC<sub>s</sub>. However, contrasting effects on the emission intensity from feed purchases were observed, increasing these emission sources by 61% (0.09 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>) in EC<sub>s</sub> and by 110% (0.14 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>) in the AC<sub>s</sub>. As for the N losses, it is essential to highlight the baseline characteristics of the purchased fraction of the diet in each DPS. While in the AC<sub>s</sub> the CP content was 14%, in the EC<sub>s</sub> this value was notably higher (23%). As demonstrated by previous authors, dairy cows fed with high protein content concentrates (EC<sub>s</sub>) lead to a higher N excretion (Mulligan et al. 2004). Our results confirm previous findings showing an increase of 13% in the NH<sub>3</sub> emissions (0.70 g N kg milk<sup>-1</sup>) from EC<sub>s</sub> while in the AC<sub>s</sub> these emissions were reduced by 0.25 g N kg milk<sup>-1</sup> (-8%). This increase in NH<sub>3</sub> emissions directly affects indirect N<sub>2</sub>O emissions associated with manure management and fields. As indicated by previous authors, higher NH<sub>3</sub> increases indirect N<sub>2</sub>O emissions (Nevison 2000; Martins et al. 2015). The obtained modelling outputs are consistent with these findings, showing an increase of 0.004 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in the indirect N<sub>2</sub>O sources only in the case of EC<sub>s</sub>. As for the rest of the N losses (NO<sub>3</sub><sup>-</sup>, N<sub>2</sub>O, and NO<sub>x</sub>), reductions were observed in both DPS. According to the obtained results, the overall effectiveness of the tested mitigation options must be assessed from a holistic perspective. As mentioned by previous authors and further demonstrated by our results, the increase in concentrate supply can lead to undesirable negative trade-offs at the whole-farm scale (Wilkinson et al. 2019). In this context, diversified and integrated forage systems with high-quality silages have proven to be a feasible alternative to concentrates as they allow for better productivity without compromising the environmental performance of the farms, at the same time that they



promote circularity and reduce food-feed competition (Gislou et al. 2020; Gaudaré et al. 2021; Díaz de Otálora et al. 2022).

Reducing the CP content of the purchased diet fraction significantly decreased the total  $N_{\text{int}}$  from  $WC_i$ ,  $EC_s$ , and  $NC_s$ . The observed mitigation potential for N losses was more significant in the  $WC_i$  and the  $EC_s$  than in the  $NC_s$ , with reductions of 1.3 (-16%), 1.2 (-16%) and 0.7 (-6%) g N kg milk<sup>-1</sup>. As for the  $GHG_{\text{int}}$ , emissions were mitigated from 0.02 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in  $NC_s$  to 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in  $EC_s$ . N<sub>2</sub>O emissions from manure management (direct and indirect) and the fields (indirect and direct) were reduced to a larger extent in all DPS. In the case of the  $WC_i$ , these emissions were reduced by 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, by 0.02 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in the  $NC_s$  and 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in the  $EC_s$ . This was primarily due to the effect of CP reduction on NH<sub>3</sub> emissions. Such values were mitigated by 1.3 (-31%), 1.2 (-23%), and 0.6 (-9%) g N kg milk<sup>-1</sup> in the  $WC_i$ ,  $EC_s$ , and  $NC_s$ , respectively. Regarding other N sources, both DPS showed lower values from the yards, housing, storage, and the fields. Moreover, the N<sub>2</sub>O reduction observed has been previously described as a positive synergy derived from a better N use efficiency and lower NH<sub>3</sub> excretion (Powell and Rotz 2015). In this sense, as described by previous authors and confirmed by our results, lowering the CP content mitigates NH<sub>3</sub> emissions early in the manure management chain by reducing the amount of N supplied (Sajeev et al. 2018b). Additional to the amount of N excreted, a reduced ratio between urinary and dung N is favored, which lowers the ratio between TAN and organic N, thus decreasing NH<sub>3</sub> losses (Kebreab et al. 2001; Sajeev et al. 2018a, b). Lastly, while CP reduction mitigates N losses (mainly NH<sub>3</sub> and N<sub>2</sub>O), its effects on animal productivity must be further considered to ensure that nutritional needs are met, and unintended consequences on production levels are avoided (Del Prado et al. 2013a). As for the suitability of this mitigation option, DPS with a higher CP content ( $WC_i$  and  $EC_s$ ) have a higher mitigation potential than those with a lower baseline CP content ( $NC_s$ ). In this sense, a comprehensive diet composition analysis is crucial to identify for which DPS the reduction of CP content leads to the most significant emission reduction.

### **3.2.2. Slurry management and fertilizer application**

Implementing high-efficiency rigid slurry storage covers (HES<sub>c</sub>) in  $WC_i$ ,  $WO_s$ ,  $MC_i$ , and  $AC_s$  was associated with a decrease in  $N_{\text{int}}$  from all DPS, except  $MC_i$  where a marginal increase was observed (>1%). The observed  $N_{\text{int}}$  mitigation was due to the favourable effect of rigid covers when reducing NH<sub>3</sub> and N<sub>2</sub>O from storage (Berg et al. 2006). Our results confirm previous authors findings by showing reductions of storage N losses ranging from 0.27 (-47%) in the  $WC_i$ , to 0.06 (-23%) g N kg milk<sup>-1</sup> in the  $AC_s$ . However, a negative trade-off was observed with field

emissions, which increased in all DPS ranging from 0.20 g N kg milk<sup>-1</sup> in MC<sub>i</sub> and 0.02 g N kg milk<sup>-1</sup> in EC<sub>s</sub>. As mentioned by previous authors, covered slurry tanks are associated with lower TAN losses (Baldé et al. 2018). Therefore, higher TAN content in the slurry after storage could increase N losses in the following steps manure management chain (field application) (Pedersen et al. 2021). Our results confirm these higher emissions, especially in those DPS with larger slurry storages and manure application (MC<sub>i</sub>). However, rigid covers are a good mitigation option of direct and indirect manure N<sub>2</sub>O emissions. These reductions ranged from 0.008 to 0.002 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> for the direct emissions and from 0.003 to 0.0004 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> for the indirect N<sub>2</sub>O. These findings were associated to the relative environmental advantage of rigid covers over other options (i.e., open with crust), which is expressed in the SIMS<sub>DAIRY</sub> model by a lower EF (Del Prado et al. 2011). Lastly, no emission reductions were observed in CH<sub>4</sub> emissions from manure. Overall, HES<sub>c</sub> are presented as effective option to reduce GHG and N emissions, especially during manure storage (Viguria et al. 2015; Kupper et al. 2020). Compared to permeable or semi-permeable membranes, completely sealed covers significantly reduce N losses and GHG emissions (Montes et al. 2013). Although there is no variation in CH<sub>4</sub> emissions, several studies have attributed promising results in reducing this gas after applying this type of cover (Reis et al. 2015; Zhang et al. 2021). Furthermore, the negative trade-offs observed after the application of this measure (i.e., higher field emissions) could be mitigated by the combination with additional measures during storage (acidification), by improving application techniques (i.e., injection), or by reducing the N application rate (Fangueiro et al. 2018; Pedersen et al. 2022). This would be especially advisable in those intensive systems where the production and application of slurry as organic fertilizer is more prominent (WC<sub>i</sub> or MC<sub>i</sub>).

Shallow slurry injection (HES<sub>a</sub>), implemented in EC<sub>s</sub>, MC<sub>i</sub>, and NC<sub>s</sub>, increased the GHG<sub>int</sub> of MC<sub>i</sub> by 0.02 (1%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup> while reducing the GHG<sub>int</sub> of EC<sub>s</sub> and NC<sub>s</sub>. Furthermore, increased direct N<sub>2</sub>O emissions from fields were observed in the MC<sub>i</sub> (9% or 0.03 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>). In contrast, indirect N<sub>2</sub>O emissions from fields were reduced in all DPS, ranging from 0.005 to 0.002 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, presenting a greater mitigation potential in the EC<sub>s</sub> (-13%). No variations were observed for the rest of the GHG. As for N<sub>int</sub>, reductions ranged from 0.8 (-7%) g N kg milk<sup>-1</sup> in the NC<sub>s</sub> to 0.4 (-5%) in the WC<sub>i</sub>. The breakdown of N emissions showed mitigation of NH<sub>3</sub> emissions in all DPS, being especially relevant in MC<sub>i</sub> with 0.95 g N kg milk<sup>-1</sup> (-19%). In contrast, this measure led to an overall increase in NO<sub>3</sub><sup>-</sup> leaching and N<sub>2</sub>O emissions in the MC<sub>i</sub>. In contrast, all DPS reduced their N emission from the fields, reaching a reduction of 0.8 g N kg milk<sup>-1</sup> (-10%) in the case of the NC<sub>s</sub>. As described by previous studies and demonstrated by our results, HES<sub>a</sub> could be associated with lower NH<sub>3</sub> and indirect N<sub>2</sub>O

emissions but higher direct N<sub>2</sub>O emissions (Rodhe et al. 2006; Bessou et al. 2010; Langevin et al. 2015). Our results align with those described by previous authors (Herr et al., 2019), as indirect N<sub>2</sub>O emissions reductions may derive from less NH<sub>3</sub> volatilization (Räbiger et al. 2020). Further mitigation of the field emission could be achieved through the use of nitrification inhibitors as a way to reduce both NH<sub>3</sub> and N<sub>2</sub>O losses (Fan et al. 2022). Overall, our results indicate that although there was an increase in the total N<sub>2</sub>O emission intensities in the modelled DPS, this increase was not significant enough to offset the reductions in other forms of nitrogen emissions (i.e., NH<sub>3</sub>). However, it is advisable to adjust the dose of fertilizer dose to avoid possible leaching and N<sub>2</sub>O emission in those DPS with high N input (MC<sub>i</sub>) (Min et al. 2012).

Urea substitution increased the GHG<sub>int</sub> of the MC<sub>i</sub> by 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (1%) while reducing by 0.0002 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (0.02%) the one in AC<sub>s</sub>. Furthermore, direct N<sub>2</sub>O emission intensity from the fields increased by 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in MC<sub>i</sub> and 0.001 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> in AC<sub>s</sub>. In contrast, indirect N<sub>2</sub>O emissions from the fields were reduced by -4% in AC<sub>s</sub> and -3% in MC<sub>i</sub>, accounting for reductions of 0.001 and 0.001 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, respectively. Regarding N<sub>int</sub>, a positive effect was observed in both DPS, being greater in AC<sub>s</sub> with a reduction of 0.1 g N kg milk<sup>-1</sup> (-2%). This mitigation was associated with lower NH<sub>3</sub> emissions, which were reduced by 0.3 (-7%) g N kg milk<sup>-1</sup> in the MC<sub>i</sub> and 0.2 (-5%) g N kg milk<sup>-1</sup> in the AC<sub>s</sub>. Even though N<sub>2</sub>O emission and NO<sub>3</sub><sup>-</sup> leaching increased, this was not large enough to offset the positive effect obtained on NH<sub>3</sub> emissions. However, emissions of these two gases were higher in the MC<sub>i</sub> than in the AC<sub>s</sub>. This may be associated with the soil texture of the MC<sub>i</sub> (sandy loam) and the higher doses of N applied, thus potentially leading to higher leaching values (Zhou et al. 2006). In this context, attention should be paid to the N source used for substitution, as the effectiveness of the mitigation option could vary (Rahman and Forrestal 2021). As demonstrated by our results, nitrate-based fertilizers increased the N<sub>2</sub>O emissions compared to urea (Harty et al. 2016). This is mainly due to the higher nitrification and denitrification potential of AN (Wrage et al. 2004) and higher TAN per ha applied to the fields considering a much lower N volatilization loss just after application. Therefore, incorporating N stabilizers or nitrification inhibitors (not considered by the current version of the model), and the optimization of fertilizer application could further decrease NH<sub>3</sub> and N<sub>2</sub>O emissions (Wang et al. 2020, 2021; Rahman et al. 2021). Overall, the increase in field NO<sub>3</sub><sup>-</sup> and N<sub>2</sub>O emissions could advise against the change to AN from a whole-farm perspective in farms with high N input and soils with a higher proportion of sand (MC<sub>i</sub>).

Lastly, implementing AD in WC<sub>i</sub>, WO<sub>s</sub>, and MC<sub>i</sub>, reduced the GHG<sub>int</sub> in all DPS with a greater mitigation potential in WC<sub>i</sub> than in MC<sub>i</sub> or WO<sub>s</sub>. In this line, the WC<sub>i</sub> showed a GHG<sub>int</sub> reduction

of 0.16 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-19%), while WO<sub>s</sub> and MC<sub>i</sub> accounted for reductions of 0.08 (-9%) and 0.12 (-7%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup>. Notable reductions were observed in manure (CH<sub>4</sub> and N<sub>2</sub>O) and energy-related (CO<sub>2</sub>) emissions. For instance, CH<sub>4</sub> from manure was reduced by 0.17 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-58%) in MC<sub>i</sub> and 0.13 (-82%) and 0.06 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-76%) in WC<sub>i</sub> and WO<sub>s</sub>, respectively. Furthermore, CO<sub>2</sub> emission intensity related to energy use was mitigated in a range of 0.023 to 0.007 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>. As for N<sub>int</sub>, differences in mitigation potential were observed across DPS with reductions of 0.3 g N kg milk<sup>-1</sup> (-4%) in WC<sub>i</sub>, and an increase of 0.6 g N kg milk<sup>-1</sup> (5%) in MC<sub>i</sub>. In contrast, field N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup> emissions were observed in all the DPS evaluated. In the same line as the results obtained for the HES<sub>c</sub> and the HES<sub>a</sub>, the higher content of TAN in the digestate, combined with a higher and more frequent organic fertilizer application, could derive in N supply above crop demand (Perego et al. 2012). Nevertheless, storage N losses were lowered in all DPS, due to the advantage of AD in reducing NH<sub>3</sub> emissions ranging from 0.4 g N kg milk<sup>-1</sup> in WC<sub>i</sub> to 0.1 g N kg milk<sup>-1</sup> in WO<sub>s</sub>. Overall, implementing AD plants was a valuable way of reducing manure storage emissions through biogas recovery systems, especially when covered digestion tanks are adopted, as considered in this study (Harrison and Ndegwa 2020; Kim and Karthikeyan 2021). Previous studies highlighted the potential of this technology in reducing GHG emissions from manure (Clemens et al. 2006; Scott and Blanchard 2021). Our results align with these findings and confirm AD effectiveness in various DPS. Moreover, the potential of this measure goes beyond emission reduction, as it can play an essential role in the circularity of farming systems through the generation of renewable energy (Holly et al. 2017; Stanchev et al. 2020). Nevertheless, special attention should be paid to using digestate as fertilizer as it could lead to higher N losses after application (Baldé et al. 2018; Aguirre-Villegas et al. 2019) unless rates from other N fertilizer forms (specially mineral fertilizer) are reduced accordingly. This was demonstrated as an especially relevant trade-off in those intensive systems with higher fertilization rates (MC<sub>i</sub>). Therefore, it is necessary to analyze the emissions from a holistic perspective assessing the possible negative interactions (i.e., pollutant swapping) associated with the single application of AD as a mitigation option.

### **3.2.3. Combined application**

In contrast to previous studies that described the effect of individual options, the applied modelling framework considered the interactions between different measures. In this way, the negative or positive effects of a particular measure could be influenced by the combined effect of two or more mitigation options (Del Prado et al. 2010; Beukes et al. 2011). This approach enabled the assessment of the suitability of a wide range of measures in different production

contexts and, as supported by our results, achieved positive emission reduction result (Vellinga et al. 2011).

Figures 1 and 2 show the single and combined effect of the selected mitigation options on each modelled DPS. For the GHG sources, enteric (CH<sub>4</sub>), manure (CH<sub>4</sub> and direct/indirect N<sub>2</sub>O), field-related (direct/indirect N<sub>2</sub>O) and emissions from other sources (CO<sub>2</sub> from feed purchases, energy use and fertilizer purchases) were considered. As for the N emission sources, yards, housing, storage, fields and silage were evaluated. Mitigation results for the full sample (in % and absolute values) are provided in Supplementary Material 3.

The combined application of HES<sub>c</sub>, CP and AD resulted in positive synergies that reduced the N<sub>int</sub> by 1.3 g N kg milk<sup>-1</sup> (-16%) and the GHG<sub>int</sub> by 0.16 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-20%) in the WC<sub>i</sub>. As shown in Figure 2, a reduction of 0.14 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-78%) in the manure-related GHG emission (CH<sub>4</sub> and direct and indirect N<sub>2</sub>O) was observed. Less prominent reductions were achieved for the emission intensity from other GHG sources (feed purchase, energy use, and fertilizer purchase), which were mitigated by 0.02 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-7%). For this DPS, no variations were observed in the enteric GHG emissions. As for the N losses, those related to manure storage were reduced by 0.46 g N kg milk<sup>-1</sup> (-83%) (due to strong reductions on NH<sub>3</sub>). In addition, emission intensity from the housing and the yards were mitigated by 0.58 (-38%) and 0.29 (-37%) g N kg milk<sup>-1</sup>. As demonstrated by our results, the joint application of the above-mentioned mitigation options in Western European conventional intensive DPS, resulted in significant reductions of GHG<sub>int</sub> and N<sub>int</sub> and created positive synergies that reduced the negative effect of measures acting separately. Overall, the selection of mitigation options for this DPS were adequate as no relevant negative trade-offs were identified, and positive synergies were enhanced (i.e., NH<sub>3</sub> manure storage emissions)

Regarding WO<sub>s</sub>, the joint implementation of HES<sub>c</sub> and AD decreased the GHG<sub>int</sub> by 0.07 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-9%) and 0.09 g N kg milk<sup>-1</sup> (-2%) the N<sub>int</sub>. The reduction in GHG<sub>int</sub> was mainly associated with emissions from manure (CH<sub>4</sub> and N<sub>2</sub>O) which were mitigated by 0.06 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-68%) and the fields (N<sub>2</sub>O) with a reduction of 0.004 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-9%). To a lesser extent, the combined action of the mitigation measures resulted in a reduction in other GHG sources, mostly associated with emissions intensity from energy use of 0.01 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-2%). Regarding the breakdown of N emission sources, emissions from the storage were mitigated by 0.13 (-42%) g N kg milk<sup>-1</sup>. This result was expected because both mitigation measures significantly reduced NH<sub>3</sub> emissions during the manure storage period. In the case of organic systems, the applicability of diet-oriented measures is limited due to the requirements of

the production system. Likewise, this same production system limits the number of improvements made at the field scale (i.e., mineral fertilizers). For this reason, the joint implementation of the proposed mitigation options is effective and feasible for semi-extensive organic systems, while future modelling exercises should explore the possibility of increasing the forage quality to enhance the milk yields.

The combined application of PI, CP, and HES<sub>a</sub> resulted in an -6% (0.08 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>) reduction of the GHG<sub>int</sub> and a -32% mitigation (2.3 g N kg milk<sup>-1</sup>) of the N<sub>int</sub> for EC<sub>s</sub>. While enteric (CH<sub>4</sub>), manure (CH<sub>4</sub> and N<sub>2</sub>O), and field (N<sub>2</sub>O) emissions were reduced by 0.05 (-11%), 0.05 (-19%), and 0.06 (-15%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, an increase in emissions from other sources (0.1 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>), mainly associated with CO<sub>2</sub> emissions from feed purchases. Regarding the N emissions sources assessed, the combined application of measures significantly reduced emissions in all sources assessed. The results showed how the negative trade-offs associated with the single application of PI were reversed by implementing, at the same time, a reduction of CP in the purchased fraction of the diet. Our results demonstrate the effectiveness of the proposed combined tailored application of mitigation measures when the emission particularities of the farms are considered, thus preventing unwanted pollutant swapping and improving the mitigation potential. In addition, to further reduce the negative impacts of the concentrate increase, future work should address the effect of improved dietary forages to increase productivity.

Applying HES<sub>a</sub>, HES<sub>c</sub>, the substitution of urea, and the AD plant resulted in reductions of the GHG<sub>int</sub> (-4%) and N<sub>int</sub> (-3%) of MC<sub>i</sub>, accounting for 0.1 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> and 0.3 g N kg milk<sup>-1</sup>, respectively. Manure-related and external input GHG emissions (i.e., energy use) were mitigated by 0.17 (-55%) and 0.02 (-4%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup>. However, proposed mitigation options increased the direct field N<sub>2</sub>O emissions by 0.1 (39%) kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, primarily associated with urea substitution and AD (digestate application). Concerning the N<sub>int</sub>, remarkable reductions were observed in manure storage (0.34 g N kg milk<sup>-1</sup> (-57%)) mainly derived from the lower NH<sub>3</sub> emissions, which were reduced by 30% (1.5 g N kg milk<sup>-1</sup>). Furthermore, the proposed mitigation measures reduced the previously noted negative trade-offs associated with the field emissions. In contrast, the applied mitigation scheme further enhanced the emissions of N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup>, which were increased by 0.3 (36%) and 0.9 (16%) g N g milk<sup>-1</sup>, respectively. Overall, the proposed combination of mitigation strategies effectively reduced the GHG and N emissions, mainly from manure storage. However, the applied options resulted in a higher TAN content in the slurry applied to the fields, and the use of ammonium-based fertilizers could lead to higher

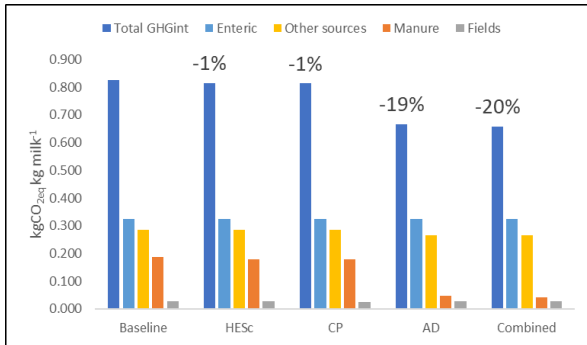
N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup> emissions. Therefore, these measures should be combined with better fertilization strategies adjusting the N input to the crop needs.

As for NC<sub>s</sub>, the effect of HES<sub>a</sub> and CP acting in combination showed a reduction in the GHG<sub>int</sub> of 0.03 kg CO<sub>2eq</sub> kg milk<sup>-1</sup> (-2%) while reducing the N<sub>int</sub> by -11% (1.4 g N kg milk<sup>-1</sup>). In terms of GHG emission sources, the manure emissions were reduced by -2% reduction (0.002 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>), the fields by -15% (0.02 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>), and no variation in the GHG emission from enteric fermentation were observed. Concerning the N<sub>int</sub>, emissions associated with the fields (-14%), yards (-14%), housing (-11%), and storage (-6%) were mitigated by 1.1, 0.12, 0.11, and 0.03 g N kg milk<sup>-1</sup>, respectively. In all, the adopted combination of mitigation measures proved to be effective in reducing both GHG and N emissions in conventional semi-extensive Northern European DPS. According to the characteristics of the farm (significant supply of concentrate), it would be advantageous to implement quality forages (legumes) that partially replace these external inputs, thus reducing the off-farm emissions.

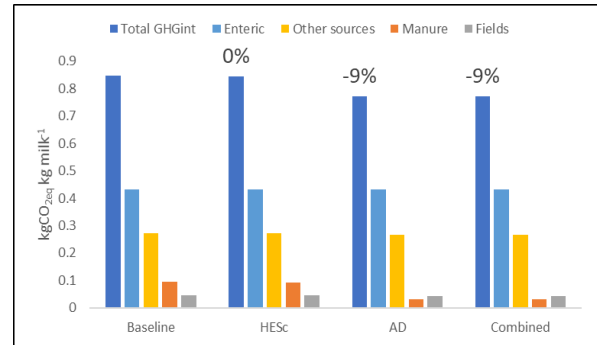
Lastly, as for the AC<sub>s</sub>, the combined application of PI, HES<sub>c</sub> and urea substitution resulted in a 5% increase in GHG<sub>int</sub> (0.04 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>) and a -15% (0.76 g N kg milk<sup>-1</sup>) reduction in N<sub>int</sub>. As for the GHG sources, significant reductions were observed in emissions intensity from enteric fermentation (-12%), the fields (-22%), and manure (-17%) with 0.06, 0.02 and 0.02 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>, respectively. However, increased supply of concentrate in the diet led to a higher emission intensity from other sources (0.14 kg CO<sub>2eq</sub> kg milk<sup>-1</sup>), mostly derived from CO<sub>2</sub> emission from feed purchases. Regarding the sources of N emissions, an increase was observed in emissions associated with the yards, which the proposed combination of measures could not mitigate. These emissions were increased by 0.2 g N kg milk<sup>-1</sup>, 53% more than the baseline. Nevertheless, the combined application is presented as a timely measure for mitigating N emissions from the fields (-18%), silage (-31%), storage (-27%) and housing (-9%) with reductions of 0.6, 0.2, 0.7 and 0.04 g N kg milk<sup>-1</sup>, respectively. Although the combined effect of the applied measures reduced the original GHG<sub>int</sub> and N<sub>int</sub> values for the conventional semi-extensive Atlantic DPS, the increase of the concentrates supply hinders the positive effect and the synergies between the different applied measures. Therefore, the application of this mitigation measure should be subject of further consideration in order to evaluate to what extent this option does not negatively affect the overall emissions of the farm. In addition, the use of slow release fertilizers (i.e., protected urea) could be a solution for further mitigation of emissions associated with the application of mineral fertilizers.

**Figure 1:** Variation of emissions from greenhouse gas (GHG) emission sources for the different dairy production systems and mitigation options evaluated. GHG<sub>int</sub> greenhouse gas emission intensity; WC<sub>i</sub> Western European conventional intensive system; WO<sub>s</sub> Western European organic semi-extensive system; EC<sub>s</sub> Central-Eastern European conventional semi-extensive system; MC<sub>i</sub> Mediterranean conventional intensive system; NC<sub>s</sub> Northern European conventional semi-extensive system; AC<sub>s</sub> Atlantic conventional semi-extensive system; GHG: greenhouse gas; N: nitrogen; HES<sub>c</sub>: high-efficiency slurry cover; HES<sub>a</sub>: high-efficiency slurry application; Urea: urea substitution; CP: low crude protein; PI: Increased productivity; AD: anaerobic digestion

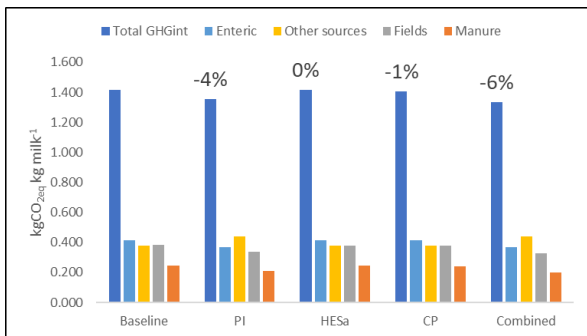
a) WC<sub>i</sub>



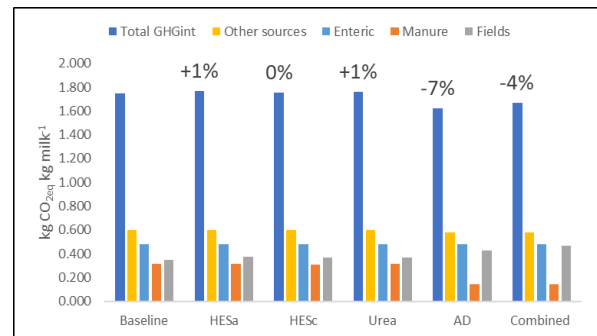
b) WO<sub>s</sub>



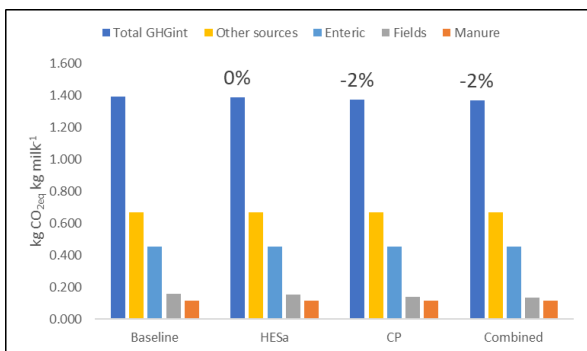
c) EC<sub>s</sub>



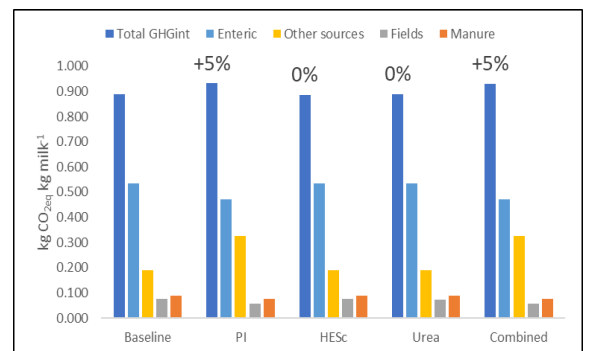
d) MC<sub>i</sub>



e) NC<sub>s</sub>



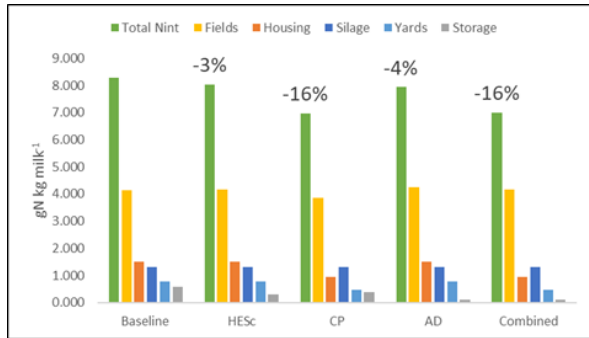
f) AC<sub>s</sub>



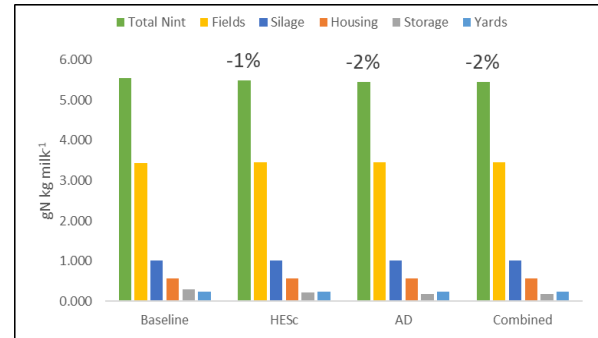


**Figure 2:** Variation of emissions from nitrogen (N) emission sources for the different dairy production systems evaluated and mitigation options applied.  $N_{int}$  total nitrogen emission intensity;  $WC_i$  Western European conventional intensive system;  $WO_s$  Western European organic semi-extensive system;  $EC_s$  Central-Eastern European conventional semi-extensive system;  $MC_i$  Mediterranean conventional intensive system;  $NC_s$  Northern European conventional semi-extensive system;  $AC_s$  Atlantic conventional semi-extensive system; GHG: greenhouse gas; N: nitrogen; HES<sub>c</sub>: high-efficiency slurry cover; HES<sub>a</sub>: high-efficiency slurry application; Urea: urea substitution; CP: low crude protein; PI: Increased productivity; AD: anaerobic digestion.

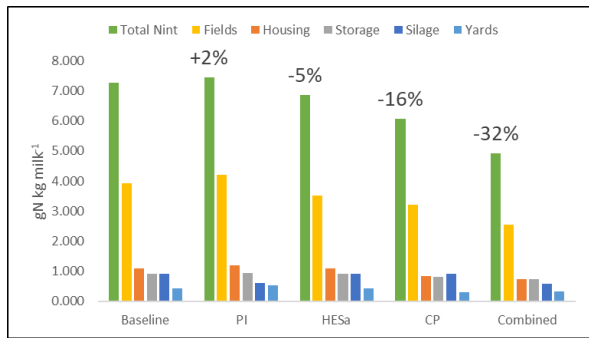
a)  $WC_i$



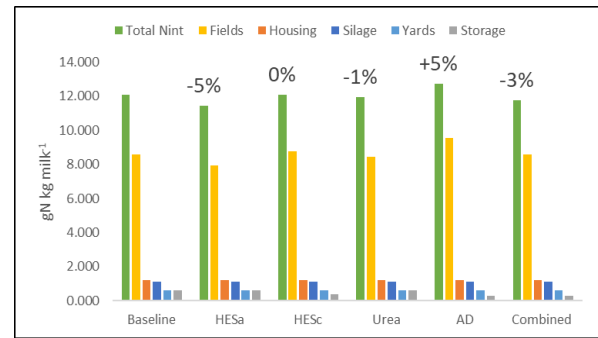
b)  $WO_s$



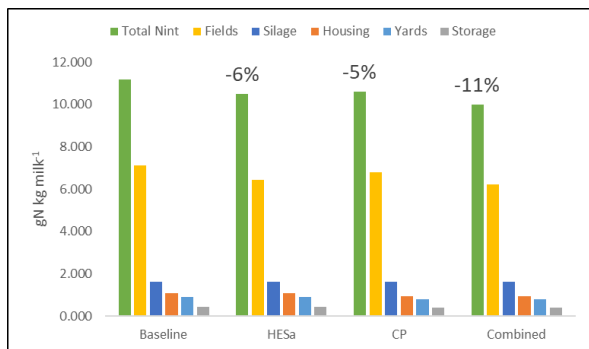
c)  $EC_s$



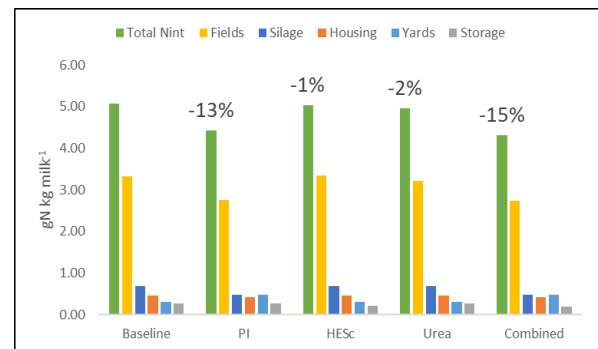
d)  $MC_i$



e)  $NC_s$



f)  $AC_s$



#### 4. Conclusions

As demonstrated in this study, the existing diversity of DPS across Europe plays a crucial role in GHG and N emission intensities and the mitigation potential of emission reduction options. Through process-based modelling approaches applied to key DPS typologies, we assessed the single and combined effect of adapted emission mitigation options on intensive, semi-extensive, conventional, and organic DPS across Europe. In this way, our results allow for the identification of the most appropriate options according to the particularities of the systems.

Reducing the CP content of the purchased fraction of the diet was an advisable option to reduce both GHG and N emissions independently of the production system. However, AD reduced GHG emissions in all cases (especially from manure storage), with undesirable trade-offs in the field N emissions from intensive Mediterranean farms due to higher TAN content on the slurry. Similarly, opting for rigid slurry covers reduced storage  $\text{NH}_3$  volatilization while increasing N losses from the fields proportionally to the farm intensity. In this sense, considering the whole manure management chain when implementing this option is crucial. In contrast, shallow slurry injection notably reduced N losses associated with fields, showing higher mitigation potential in the Mediterranean intensive than in semi-extensive Northern and Central-Eastern European DPS. Regarding the substitution of urea, overall N losses were reduced while discouraging this option for systems with sandy-loam soils due to higher  $\text{N}_2\text{O}$  and  $\text{NO}_3^-$  emissions. Finally, while lowering the F:C ratio can lead to an overall reduction of GHG emissions, a whole-farm perspective must be adopted to capture the potential increase of N losses in systems with a high CP in the baseline diet. Furthermore, our results represent a novel contribution to the analysis of emission mitigation potential across European DPS when mitigation measures are applied in combination. Positive synergies were promoted, and negative trade-offs were eliminated by combining CP and F:C ratio reductions. In addition, the joint application of slurry covers and shallow injection was a suitable combination for reducing emissions from both intensive and semi-extensive systems.

This study contributes to a better understanding of the emission reduction potentials in European farming systems for dairy production, setting the base for applying adapted concepts, strategies and policies. As demonstrated by our results, the future sustainability of DPS largely relies on optimizing farm processes by adopting tailored combinations of mitigation measures, with particular emphasis on reducing emissions and improving efficiency by avoiding reliance on external feeds or inputs. In this context, the model needs to further assess the use of quality forages and adapted fertilization plans. Future developments should contemplate these aspects in

more detail by analyzing the interactions between different production systems (livestock-crop) and their effect on environmental, economic, and social sustainability.

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# Chapter 7: General discussion

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Analyzing the sustainability of key European dairy cattle production systems (DPS) from a holistic perspective allows for the adapted mitigation of their environmental impact while ensuring their economic and social feasibility. To this end, this Ph.D. Thesis presented solutions to some of the main challenges that DPS face based on four pillars of action:

1. Facilitating decision-making in terms of model selection for the determination of integrated sustainability.
2. Analyzing the diversity of production systems across Europe.
3. Assessing the influence of farm characteristics and management practices on GHG and N emission sources from DPS across Europe.
4. Evaluating the effect of adapted mitigation measures for greenhouse gas (GHG) and nitrogen (N) emissions considering the diversity of DPS.

The following chapter will discuss the results obtained from the different investigations carried out during the Ph.D. Thesis. In addition, the implications of the results in the current scenario and the future research avenues are addressed.

### **1. Facilitating the analysis of integrated sustainability**

As of today, the availability of appropriate methods and tools for the sustainability assessment of different livestock systems has been a significant challenge for the scientific community (Chopin et al. 2021; Alary et al. 2022). Although several tools are available to analyze sustainability through various methods and approaches (Arulnathan et al. 2020), many are developed to explore specific attributes (i.e., emissions, economic performance, etc.), thus limiting their suitability for integrated sustainability assessments. Furthermore, models and tools assess the interactions and relationships between sustainability pillars to a limited extent, presenting multiple constraints when analyzing sustainability from a holistic perspective. The combination of these facts hampers a comprehensive comparison between the tools and hinders adapted the decision-making process at the systemic scale (Gibson 2009).

The successful assessment of the sustainability of DPS largely relies on the tools applied. This process must start with the considerate selection of the most appropriate approach used for each of the particular circumstances. This requires a comprehensive evaluation of the level of detail with which attributes from the three sustainability pillars are integrated. Therefore, the development of specific frameworks that consider social, economic, and environmental sustainability aspects associated with the different systems that constitute DPS is necessary. To this end, this Ph.D. Thesis built, described, and tested an indicator-based quantitative framework

aimed at whole-farm models for integrated sustainability assessments. To this end, 35 indicators describing sustainability from the economic, social, and environmental aspects were included. In addition, 3 previously described whole-farm scale sustainability assessment models were used as a basis for testing the evaluation framework: Sustainable and Integrated Management Systems for Dairy Production (SIMS<sub>DAIRY</sub>), Global Activity Model for Evaluation of the Sustainability of Dairy Enterprises (GAMEDE), and the Weighted Linear Goal Programming Model for Dairy Farms (WLGPF).

The evaluation framework presented in this Ph.D. Thesis identified the environmental pillar as the one that achieved greater detail by the models. In this regard, while indicators related to land use and resource consumption (i.e., water and energy) were widely considered, farm management practices were incorporated with varying levels of detail (i.e., grazing, fertilizer use, cutting strategy, etc.). As mentioned by previous authors, analyzing these practices is crucial for determining the environmental sustainability of farms (Clay et al. 2020). Furthermore, the integrated sustainability assessment would benefit from a detailed analysis of the emission magnitudes and sources derived from farming activity. As described in the literature, considering these aspects would contribute significantly to the usefulness of the models as a deeper understanding of the farm processes will be enabled and the application of specific sustainability measures will be facilitated (Rotz 2018).

Integrating approaches to assess economic attributes while analyzing the environmental and social features of a DPS is complex. Moreover, the different dynamics contemplated by models, mostly focused on environmental sustainability, cannot be introduced analogously when assessing farm economics. In this context, the results of this Ph.D. Thesis explored the suitability of the tools evaluated to address the most significant features of the economic sustainability of DPS. Although the models well represented aspects related to productivity and farm income, more emphasis should be placed on incorporating indicators associated with the diversification and quality of the economic products and services derived from farming activity. Previous studies acknowledge that these indicators are associated with farm competitiveness (García-Cornejo et al. 2020; Hochuli et al. 2021). The models would benefit from their incorporation, as more comprehensive economic sustainability assessments could be enabled. Likewise, none of the models evaluated incorporated attributes related to farm durability. This aspect has been described in the literature as one of the main drivers of farm continuity, particularly in smaller holdings (Lebacqz et al. 2013; Cassidy and Mcgrath 2014). Further development of the models

would require a deeper understanding of the economic drivers that condition farmer behavior to assess DPS economic durability.

Moreover, the proposed evaluation framework allowed for pointing out a clear imbalance in the level of representation of the social aspects of sustainability. These results align with the previous author's findings, thus presenting the social pillar as the least described in sustainability assessments (Chen and Holden 2017). Compared to the level of detail with which environmental and economic aspects were analyzed, assessing the social implications of DPS remains an overall challenge for sustainability assessment models. Although some evaluation frameworks (i.e., Sustainability Assessment of Food and Agriculture-SAFA from FAO) have evaluated this pillar of sustainability in some livestock systems (i.e., small ruminants) (Paraskevopoulou et al., 2020), generalizing social sustainability assessments to dairy cattle farms and different production contexts is still a challenge. Furthermore, in a context of increasing interest regarding the impact of dairy production on society (Ly et al. 2021), the underrepresentation of this pillar limited the drawing of conclusions regarding the integrated sustainability of DPS. To this end, implementing specific approaches (i.e., participatory approaches) has been described as a possible way to disentangle some of the social challenges affecting sustainability and the design of meaningful future policies (Hugé 2017).

Although the presented results quantitatively assessed the level of detail with which models address aspects of DPS's economic, social, and environmental sustainability pillars, future studies should consider the qualitative perspective in the framework. As mentioned by previous authors, including this qualitative participatory perspective will cooperate to identify critical drivers that condition the transition toward sustainability (Gerber et al. 2013; Trigo et al. 2021). Despite these limitations, the results of this Ph.D. Thesis are presented as a significant contribution towards implementing knowledge-based decision support tools to evaluate the modelling approaches for the integrated sustainability DPS.

## **2. Assessing the diversity of DPS at the European level**

The combination of socio-economic factors, climatic conditions, structural characteristics, and environmental impacts shape the DPS across Europe. As a result, dairy production is highly diverse and varies significantly between European regions (European Parliament 2018). Furthermore, land use for dairy and fodder crop production divides the European territory into multiple productive contexts. Far from being a limitation, this diversity of systems allows for the application of adapted measures to the particular needs of each production context. In this way,

it is possible to improve productive efficiency while reducing the environmental impact of DPS. However, identifying and analyzing this diversity remains challenging, given the absence of context-specific approaches. This fact burdens the assessment of the sector's complex reality and hinders the guiding capacity of policymakers and advisors (Ahikiriza et al. 2021).

To date, several studies have tried to tackle the assessment of the DPS diversity by focusing on particular aspects of dairy production creating (e.g., farm intensification, economic attributes, etc.) (Gonzalez-Mejia et al. 2018; Poczta et al. 2020), thus limiting the scope and applicability of the identified typologies. In this context, a joint analysis of different environmental and socio-economic aspects is advised to understand the sector across Europe better. In addition, the current knowledge gap regarding the relationship between DPS and fodder crops at the regional scale in Europe has prevented the determination of representative and region-specific DPS typologies. All this hampers scientists and policymakers from developing targeted measures and policies based on a better knowledge of the diversity of existing systems. To this end, the research carried out in this Ph.D. Thesis allowed for the identification and analysis of representative typologies of dairy and fodder crop production systems at the NUTS2 (Nomenclature of Territorial Units for Statistics) regional scale in Europe. Following a novel multivalent statistical approach, the results clustered over 250 NUTS2 regions across Europe according to 16 representative dairy-fodder crop production system typologies.

In contrast to the previously mentioned typology analysis, the methodology followed in this Ph.D. Thesis considered the socio-economic and environmental attributes of DPS in a joint manner. As highlighted by previous authors, this is presented as a critical step for the success of strategies to promote sustainability in dairy farms (Toro-Mujica et al. 2020; Grassauer et al. 2022). Likewise, in line with several studies, the system approach followed is presented as an effective way to address context-specific sustainability trade-offs (Ahmadzai et al. 2021; Diogo et al. 2022). On top of that, the efficacy of emissions mitigation measures largely depends on the context in which they are applied (Duffy et al. 2021). To this end, the diversity of indicators and the regional perspective used in Ph.D. Thesis cooperates to overcoming the existing barriers in implementing adapted environmental sustainability options (i.e., emission mitigation, circularity, etc.). In this way, and in line with previous authors, the uncertainty when applying sustainability strategies could be reduced by better addressing the diversity and specificity of particular production systems (Duffy et al. 2021; Siemons et al. 2023).

Furthermore, the findings of this Ph.D. Thesis highlight the potential of European regions for integrating dairy and fodder crop production systems (mixed farming systems). Despite the lack

of specific indicators at the European level, the novel methodology applied in this Ph.D. Thesis opens the door for the analysis of this level of integration using *ad-hoc* metrics and approaches. In this context, as demonstrated by previous work, implementing mixed farming systems would reduce dependence on external inputs while favouring the preservation of resources and ecosystems (Coquil et al. 2014; Reinsch et al. 2021). Furthermore, the results presented allow for optimized use of the inputs, adapting the production to the particularities in each region. As already described by other authors, a recoupling productive system will be linked to enhanced efficiency in the use of resources (Regan et al. 2017). Lastly, in the context of mixed farming systems and consistent with previous authors' claims, this Ph.D. Thesis facilitates the future development of concepts tailored to each productive scenario allowing the implementation of adapted policies (Bijttebier et al. 2017).

The results obtained in this Ph.D. Thesis provide supporting evidence on how a better understanding of the diversity DPS in Europe could allow for the adaptation of sustainability policies and strategies. Moreover, these results make substituting "one-fits-all" solutions with adapted tailor-made concepts possible. In addition, current findings could be extended by including more adapted and specific indicators for assessing integrated production systems in the analysis. This is an underlying challenge associated with the existing databases as the lack of more detailed data hampers a more detailed assessment of the integration of dairy and fodder crop systems at a regional scale.

### **3. Assessing the influence of DPS diversity of GHG and N emissions sources**

Further developing the knowledge regarding the effect of structural characteristics and management practices on the most relevant GHG and N emission sources is vital for implementing effective mitigation strategies that promote the environmental sustainability of DPS. In this line, previous authors have tackled the functional relationships between particular emission sources in a farm (i.e., manure) (Hempel et al. 2016). However, a systemic approach would enable a more detailed analysis of the interactions between emissions sources, thus allowing for the adaptation of the measures applied.

To further adapt sustainability measures (i.e., circularity and crop-livestock integration) and address the effect of DPS particularities in emission sources, this Ph.D. Thesis identified and assessed the interactions of four different categories of management practices and structural characteristics on GHG and N emission sources from key dairy farm typologies in Europe. As for the climatic characteristics, this Ph.D. Thesis highlighted their role as critical factors when

shaping emissions, mainly from manure management. These findings align with previous results, describing a direct correlation between ambient temperature and higher GHG emissions (Poteko et al. 2019; Qu and Zhang 2021). In this sense, although the model used in this Ph.D. Thesis only considered the ambient climatic data, previous studies have pointed out the importance of accounting for the physical characteristics (i.e., temperature) of manure during storage (VanderZaag et al. 2010). Although considering the physical characteristics of the manure would require a much greater availability of data (sometimes difficult to obtain), its incorporation will allow for a more detailed analysis of the key drivers that determine the emissions of this source.

A second key relation identified in this Ph.D. Thesis refers to the correlation between specific diet characteristics and emissions from enteric fermentation and manure management chain (storage and application). The results show how DPS that largely relied on concentrates (i.e., higher digestibility, higher crude protein content and lower fiber) presented lower emission values for the sources mentioned above. Furthermore, this confirmed the existing narrative and highlighted the role of diets as key drivers of emissions at the animal and manure level (Van Wyngaard et al. 2018; Huhtanen et al. 2021). Lastly, the results showed a clear relationship between low-efficiency fertilization practices with a notable increase in GHG and N emissions. Among the methods evaluated, the broadcast of slurry and the use of urea-based fertilizers were directly correlated with both GHG and N field emissions. On the contrary, shallow slurry injection and non-urea-based fertilizers were associated with lower emissions from this source. These results confirm previous findings, which associate the broadcast of slurry and urea application with higher N losses, mainly as  $\text{NH}_3$  emissions (Bourdin et al. 2014; Skorupka and Nosalewicz 2021).

Moreover, as facilitated by this Ph.D. Thesis, a deeper understanding of the influence of different management options and farm characteristics (i.e., fertilizer use, stocking rate, and feed purchased) on animal, manure, and field emissions could enable the design of mitigation options based on integrated practices framed in the circular economy. In this line and as acknowledged by previous authors, assessing the interactions between emission and farm components could enhance resource efficiency and offset emissions, among other benefits (Regan et al. 2017; Wiesner et al. 2020). In addition, these practices could reconnect livestock with cropping systems, providing locally produced feeds and fertilizers and reducing the imports from outside the area of influence of the farm (Billen et al. 2021). The results obtained from this Ph.D. lay the foundation for these measures by addressing emissions from a systemic and integrated



perspective, thus identifying a relevant focus for implementing circularity practices to mitigate emissions in DPS across Europe.

In all, this Ph.D. Thesis expands the current understanding regarding the effect of management practices and structural characteristics on GHG and N emission sources across different DPS in Europe. Likewise, these findings have significant implications for designing and implementing mitigation options based on integrated practices framed in the circular economy.

#### **4. Adapting emissions mitigation options**

Emission mitigation in DPS is presented as a focus for action to reduce the environmental impact and thus promote the overall sustainability of the sector (Peterson and Mitloehner 2021). Adapted feeding strategies, improved manure management options, renewable energy sources, or more efficient fertilizers are commonly considered effective GHG and N emission reduction strategies (de Vries et al. 2019; Fang et al. 2020; Villarroel-Schneider et al. 2022). Furthermore, combining more than one strategy along the livestock and management chain can significantly reduce emissions and cooperate for a more sustainable and environmentally sustainable sector.

As recommended by previous studies, homogeneous application of options for emission mitigation is discouraged, thus advocating for the implementation of tailored practices adapted to the diversity and particularities of each production context (Chmelíková et al. 2021). The results presented in this Ph.D. Thesis tested the effect of the adapted application of emission mitigation options on the most relevant GHG and N sources from a wide diversity of production systems across Europe. Furthermore, in line with previous findings (Hawkins et al. 2021), the results of this Ph.D. Thesis demonstrates the varying effects of the same emission mitigation option on different emission sources. Therefore, the presented assessment of the positive synergies or negative trade-offs of the measures applied, enables future knowledge-based decisions to be taken.

Among all the mitigation options evaluated in this Ph.D. Thesis, reducing the crude protein content of the purchased fraction of the diet resulted in a mitigation of the GHG and N emissions along the manure management chain (i.e., housing, storage and field application). The results obtained in this Ph.D. Thesis were in line with the ones found in existing literature, which established a direct correlation between CP content and N excretion at the animal level (Dijkstra et al. 2011; Sajeev et al. 2018). The implementation of an anaerobic digestion plant reduced the GHG in all scenarios while increase the N losses from the fields in intensive farms with high N input. Furthermore, in a context of an increase of energy prices, these results confirmed previous

findings concerning the potential of this measure to reduce emissions from the manure storage (Scott and Blanchard 2021) while increasing the energy sufficiency of the farms. As for implementing rigid covers on the slurry storage, these significantly reduced N losses associated with the storage phase in all scenarios without deriving in negative trade-offs on the GHG emission profile. This results align with the literature confirming a reduction in the N losses, notably associated with lower ammonia (NH<sub>3</sub>) emissions (Wyer et al. 2022). However, although the increase in CH<sub>4</sub> emissions from covered manure storage facilities is a negative trade-off commonly described in the literature (anaerobic conditions) (Zhang et al. 2021), the current limitations of the model applied in this Ph.D. Thesis prevented its identification.

When milk performance was increased due to a purchased fraction of the diet (i.e., concentrate), shallow injection for slurry was used, or urea was substituted with ammonium nitrate (AN), contradictory effects in GHG emissions and N losses were observed. As for the increase in productivity, a generalized reduction of most GHG and N emission intensity sources was noted. Despite this positive effect, carbon dioxide (CO<sub>2</sub>) emissions associated with concentrates purchases were higher, resulting in a negative balance of GHG emissions. Our results confirm those obtained by previous trials in intensive farms, which reported higher off-farm CO<sub>2</sub> emissions when using concentrates compared to other farming systems (Gross et al. 2022). As for the substitution of broadcast by injection for slurry application, the results of this Ph.D. Thesis modelled a reduction of N losses, mainly NH<sub>3</sub> from the fields, while GHG emissions increased due to higher nitrous oxide (N<sub>2</sub>O) emissions, particularly in intensive Mediterranean farms. This negative trade-off has been extensively described in recent meta-analyses (Emmerling et al. 2020) and highlighted the need for more tailored application (i.e., depth of application) or combination with other practices (i.e., better timing or use of nitrification inhibitors) (Hunt et al. 2019; Schreiber et al. 2022). When substituting urea with AN, N losses were reduced. However, increased GHG emissions were noted mainly derived from higher values on the N<sub>2</sub>O and NO<sub>3</sub><sup>-</sup>. In line with previous studies, reducing this negative effect could benefit from using advanced fertilizers with urease inhibitors or coating treatments (Forrestal et al. 2019; Dawar et al. 2021). Likewise, the combined application of mitigation measures proved to be effective in reducing the negative trade-offs observed after the individual application of measures, especially with these are adapted to the particularities of the DPS. This confirms the results obtained by previous studies, and highlights the need to mitigate emissions from a whole-farm perspective by combining strategies to reduce undesirable effects (Prudhomme et al. 2020).

This Ph.D. Thesis significantly contributed to a growing body of evidence that discouraged the uniform application of mitigation measures as it could lead to undesirable interactions such as pollution swapping. The results show how adapting mitigation measures to different farm contexts and typologies could minimize these trade-offs and foster positive synergies. In addition, the present Ph.D. Thesis represents one of the first works that addressed the combined and tailored application of mitigation measures in a wide variety of farm typologies in Europe as a successful way to reduce the negative impact of DPS across the continent.

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# Chapter 8: General conclusions

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The results obtained through the different studies carried out in this Ph.D. Thesis allows for drawing the following conclusions:

1. In Chapter three the development and implementation of quantitative evaluation frameworks allowed for the analysis of the degree to which farm-scale models incorporate the three pillars of sustainability (economic, social, environmental), identifying the most appropriate tools according to the user needs.
2. Chapter three allows for the identification of the systematic under-representation of the social dimension in sustainability assessments for dairy cattle production systems (DPS). The further consideration of this pillar by the models as well as the participation of stakeholders throughout the sustainability process, would allow for a more robust evaluation of the sustainability.
3. The integrated analysis of DPS and fodder crops through multivariate statistical approaches carried out in the Chapter four allows for the identification of 16 representative system typologies at the European regional scale. Different combinations of farming intensity, milk productivity, and forage crops (i.e., permanent and temporary grasslands, arable crops, and leguminous fodder crops) constitute the typologies identified. This enables adapted decision-making, the design and implementation of measures to promote sustainability, and the promotion of positive socioeconomic interactions.
4. In Chapter five, the combined analysis of the structural characteristics and management practices together with the main emission sources in DPS facilitates the identification of key hotspots for emission reductions (i.e., manure management, enteric fermentation and the fields).
5. The recoupling of dairy and crop production system benefits from a comprehensive analysis of the drivers conditioning emissions. In Chapter five, adapted and context-specific circularity practices are facilitated by reducing the environmental impact and promoting the overall sustainability. In particular, enhanced feed quality (i.e., highly digestible forages), better grasslands management, improved manure application and

storage techniques, and the use of organic or low-emitting mineral fertilizers are presented as suitable strategies for the evaluated contexts.

6. The magnitude and sources of greenhouse gas (GHG) and nitrogen (N) emissions at the animal level, the manure management chain, or the fields are highly influenced by the particular characteristics and the diversity of DPS across European regions. Therefore, the implementation of context-specific and adapted measures in Chapter six is presented as win-win strategy to reduce emissions while avoiding potential negative trade-offs and interactions. In particular, the increase in productivity due to a higher purchased fraction of the diet has contrasting effects depending on the system analyzed and the concentrate provided.
7. Compared to a single application, the combined and tailored application of mitigation measures modelled in Chapter six allow for positive synergies in reducing GHG and N emissions across key DPS across Europe. By jointly applying strategies aimed at increasing productivity, better slurry management (storage and application) and the use of low-emission fertilizers, the negative effects derived from the individual application of individual mitigation measures is offset (i.e., increased concentrate in the diet).

Through novel quantitative evaluation frameworks for whole-farm models, multivariate statistical approaches for the identification of representative system typologies, and adapted mitigation measures for context-specific emission reduction, this Ph.D. Thesis significantly contributes to the promotion of economic, social, and environmental sustainability in European dairy cattle production systems.