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Research article

Towards farm-level net-zero greenhouse gas emissions: Contributions of climate mitigation actions – A study of four European crop and dairy farms

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ABSTRACT

Achieving net-zero greenhouse gas (GHG) emissions in agriculture is a central objective of climate policy frameworks such as the Paris Agreement. This study explored the feasibility and trade-offs of achieving net zero at the farm level by combining life cycle assessment with modeling of soil organic carbon (SOC) stocks. Four case-study farms, two crop and two dairy, in Italy, the United Kingdom (UK), France, and Germany, and 11 mitigation actions were assessed under two 20-year eco-design scenarios: one maintaining ≥90% of baseline productivity (PM), and one achieving net zero. The scenarios combined nature-based solutions (e.g., organic fertilization, cover crops) with technological interventions (e.g., feed additive, solar power). Estimated GHG emissions decreased greatly, but SOC sequestration alone was insufficient to achieve net zero while maintaining productivity. Under the PM scenario, the Italian, French, and German farms still emitted 51%, 62%, and 84% of baseline emissions, respectively. The UK crop farm achieved net zero under the PM scenario, but had the highest ecotoxicity impact per ha, 11% higher than that of the Italian crop farm. Mitigation effectiveness depended on soil- and crop-management practices, baseline GHG emissions, and carbon inputs. Assumptions about the 20-year amortization window, nutrient cycling, and indirect GHG emissions influenced trade-offs between environmental impacts and productivity. Net zero may be pursued more effectively through cooperation among farms at the landscape or sector level. Assessing the entire agricultural value chain, improving model calibration, and supporting long-term transitions through policies will be essential for developing climate mitigation actions adoptable across European agriculture.

1. Introduction

Climate change is a growing global concern, with 20-40% of the world's population already impacted by weather-driven events (Allen et al., 2018). Limiting global warming to 1.5 °C requires reducing global emissions of greenhouse gases (GHGs) (e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)) by ca. 8% each year from 2022 to 2034 (Tollefson, 2023). However, even if anthropogenic GHG emissions ceased immediately, there remains a 42% chance of exceeding this limit, which highlights the need to drastically reduce these emissions and increase carbon (C) sequestration in soil and plant biomass (Dvorak et al., 2022).

Nature-based solutions for C sequestration, such as reforestation, are often viewed as critical to limit global warming (Hoegh-Guldberg et al., 2018). However, offsetting only 4 years of anthropogenic GHG emissions would require reforesting 7.1 million km^2 (Roebroek et al., 2023). Given these spatial and ecological limitations, land-based C sequestration can only supplement immediate and large reductions in GHG emissions from high-emitting sectors, including agriculture.

In this context, the United Nations Paris Agreement and the European Green Deal provide overarching frameworks under which the European Union (EU) has committed to reducing GHG emissions by 55% by 2030 compared to those in 1990 (EC, 2021a). EU member states and other European countries have set ambitious national

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emission-reduction targets for 2030, such as a 40%, 55%, 65%, or 68% reduction for France, Italy, Germany, and the United Kingdom (UK), respectively (EC, 2023; Burnett et al., 2024). Most member states and the UK aim to reach by 2050 "net-zero" GHG emissions (EC, 2023), which refers to offsetting all GHG emissions with equivalent removals through C sequestration (UNFCCC, 2015). The EU's Effort Sharing Regulation (EU, 2023/857) sets a 40% collective reduction below 2005 emissions across the agriculture, transport, buildings, and waste sectors by 2030, but with no specific reduction target for agriculture (EU, 2023). However, a few member states (e.g. Germany, Denmark, Ireland) have introduced agriculture-specific emission limits into their national climate laws (Federal Republic of Germany, 2019; Danish Ministry of Food, 2021; Government of Ireland, 2021).

Agriculture emits ca. 31% of global GHG emissions and 11% of those of the EU (EEA, 2022a, b; Kazimierczuk et al., 2023). Globally, the sector is responsible for 13%, 44%, and 81% of anthropic CO_2, CH_4, and N_2O emissions, respectively (IPCC, 2019), from sources such as enteric fermentation by livestock, fertilizer applications, and manure management (EEA, 2022b; Kazimierczuk et al., 2023). Food systems are currently the main factor causing humanity to exceed planetary boundaries (Rockström et al., 2025). Dietary choices, agricultural practices, land-use allocation, and waste management strongly influence agricultural sustainability (Desmarez et al., 2025). While decreasing the proportion of animal products in human diets can greatly increase the probability of meeting global climate targets (Humpenöder et al., 2024), meeting these targets will depend on a broad set of complementary measures, including healthier and more balanced diets, higher crop yields, reduced food loss and waste, and greater emission efficiency in food production (Clark et al., 2020). Nonetheless, agricultural GHG emissions in the EU decreased by only 5% from 2005 to 2022 (EEA, 2024), which highlights the urgent need for innovation and targeted mitigation strategies in the agriculture sector. While achieving net-zero GHG emissions has become a critical long-term global goal, individual farms face challenges in meeting it due to the inherent GHG emissions and limited C sequestration capacities of most agricultural production systems (Rosa and Gabrielli, 2023).

Life cycle assessment (LCA) is a valuable methodological framework for assessing environmental impacts and mitigation strategies in agriculture. It quantifies resource use and emissions throughout the production, processing, and consumption of agricultural products (Jolliet et al., 2015). It can quantify trade-offs, such as how reducing the climate change impact may influence other impacts (e.g., eutrophication, ecotoxicity). LCA has been used to estimate the mitigation potential of practices, such as increasing production efficiency (Wang et al., 2022), shifting to plant-based diets (Ran et al., 2024), and applying innovative technologies (Goglio et al., 2020).

One way to reduce net GHG emissions in agriculture is to sequester soil organic C (SOC). Soils have the potential to sequester nearly three times the amount of C currently in the atmosphere (Lal et al., 2021; Kazimierczuk et al., 2023). SOC stocks can be monitored through soil sampling, estimated through remote sensing, and predicted through process-based modeling (Garsia et al., 2023). More than 200 models are available for predicting SOC dynamics (Le Noë et al., 2023; Paul et al., 2023). Among these, the AMG model has shown strong predictive accuracy for European cropland under different types of management (Clivot et al., 2019; Garsia et al., 2023).

Although SOC-based mitigation is complex and sensitive to environmental factors, practices such as converting to organic farming can reduce GHG emissions greatly; for example, making 25% of land on French dairy farms organic could reduce sectoral GHG emissions by ca. 9% (Lambotte et al., 2023), and a German case study estimated a similar 9% reduction per kg of energy-corrected milk after organic conversion (Gross et al., 2022). Moreover, adopting renewable energy in agriculture provides a viable route to decrease reliance on fossil fuels and reduce GHG emissions (Nsabiyeze et al., 2024). Meanwhile, reforestation actions that target degraded land are criticized for relying on single-species plantations, which store less C and support less biodiversity than natural forests do (Lewis et al., 2019). In contrast, rewilding, a conservation strategy that restores ecosystem functions, has potential to increase both C sequestration and biodiversity (Carver et al., 2021).

This study explored pathways toward net-zero GHG emissions in agriculture by combining nature-based solutions with technological innovations. We examined four farms in Italy, the UK, France, and Germany, using LCA to estimate baseline emissions and AMG to predict SOC dynamics. Because these countries represent diverse agricultural landscapes, we were able to examine implications of differing regional practices and conditions. We assessed 11 mitigation actions in two 20-year scenarios, one that maintained productivity (i.e., production per unit area (farm or ha)) and one designed to achieve net-zero GHG emissions. By estimating impacts and trade-offs of these scenarios, we aimed to identify feasible strategies that balance agricultural productivity with GHG-emission mitigation goals.

2. Materials and methods

2.1. Project overview and farm selection

This study was part of the ClieNFarms project, which aims to develop and support the adoption of locally relevant solutions to achieve climate-neutral farms across Europe. The project includes 19 experimental farms and 70 commercial farms in 12 countries that are integrated into the supply chains of major European food corporations. Farms were selected for the project based on criteria such as system type, data availability, and the potential to highlight diverse management practices. This study focused on a small sub-set of the farms: a conventional crop farm in Italy (IT), a conventional crop farm in the UK, a conventional dairy farm in France (FR), and an organic dairy farm in Germany (DE).

2.2. Data collection and farm characteristics

Each farm's manager provided data on climate characteristics, soil properties, farm-performance metrics (e.g., crop or milk yield, fertilizer use, pesticide use), and specific management practices (Tables 1, 2, and A1). Among the crop farms, the IT farm, located in the Po Valley, with a humid subtropical climate (Cfa according to the Köppen-Geiger climate classification), is a 75 ha research farm focused on C sequestration and sustainable practices in industrial tomato farming. The farm, located on basic (pH > 7) silty clay loam soils (Luvisols), produces open-field tomatoes, durum wheat, and silage maize. The tomatoes and silage maize were irrigated using pumps powered by fossil fuels. The UK farm, located on basic Cambisols in the East Midlands, with a temperate oceanic climate (Cfb), serves as a research and demonstration farm focused on sustainable farming practices, biodiversity, and habitat creation. The farm contains ca. 320 ha, of which 250 ha are cropland; this study focused on 132 ha of this cropland.

Among the dairy farms, the FR farm is located on acidic (pH < 7) Cambisols in western France, with a temperate oceanic climate (Cfb). The section of the farm selected for this study (130.5 ha) focuses on forage-feeding experiments and on reducing GHG emissions from milk production. The farm produced a mean of 7561 L milk cow^{-1} yr^{-1} in 2021. The DE farm, located on acidic Luvisols in the state of Hesse, with a humid continental climate (Dfb), is a 170.5 ha research farm that grows a variety of crops and produces most of its concentrate feed (Table 2). The farm produced a mean of 8407 L milk cow^{-1} yr^{-1} in 2021.

2.3. Life cycle assessment

We used LCA to estimate the farms' environmental impacts. According to ISO standard 14040 (ISO, 2006), LCA has four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4)

Table 1
Annual per-ha management data of the four conventional (conv.) or organic (org.) experimental crop or dairy farms studied in Italy (IT), the United Kingdom (UK), France (FR), and Germany (DE). Italics indicate crops produced on dairy farms and used as cattle feed. Abbreviations: Temp. Grass.: temporary grassland, Perm. Grass.: permanent grassland, Org.: organic, Inorg.: inorganic, Nat.: natural, Pest. a.i.: pesticide active ingredients, Irrig.: irrigation, CC: cover crop, Y: yes, N: no, fert.: fertilizer, MSW: municipal solid waste, S: slurry, M: manure.

Farm	Unit	ha	kg/no.[a]	Fertilizers (kg)				L	m^3	kg	m^3	t[c]	CC	Org. fert.
	Crop	Area	Seeds/ plants	Org. N	Inorg. N	P_2O_5	K_2O	Diesel[b]	Nat. Gas	Pest. a.i.	Irrig. water	Yield		
IT conv. crop	Maize (silage)	6.0	90	-	150	-	-	299	1440	2.4	6394	20.5	N	-
	Durum wheat	39.0	185	0.4	150	0.2	0.3	99	-	0.3	-	6.5	N	MSW
	Tomato	30.0	3500	-	172	216	180	231	1080	6.2	4820	90.0	N	-
UK conv. crop	Rapeseed	12.0	3	-	142	-	117	37	-	5.9	-	1.5	N	-
	Spring barley	24.0	185	-	99	-	103	39	-	2.3	-	5.7	Y	-
	Winter wheat	67.0	220	-	119	92	117	44	-	12.0	-	8.5	N	-
	Faba bean	29.0	325	-	-	-	88	37	-	2.2	-	3.0	Y	-
FR conv. dairy	*Maize (silage)*	36.8	90	162	31	115	203	139	-	1.3	-	13.5	Y	S + M
	Temp. Grass.	56.9	37	69	49	31	87	148	-	-	-	8.0	N	S + M
	Perm. Grass.	29.2	-	-	49	-	39	80	-	-	-	5.1	N	-
	Winter wheat	4.5	185	-	108	-	-	93	-	0.7	-	6.5	N	-
	Spring barley	3.1	185	-	104	-	-	87	-	0.9	-	6.1	N	-
DE org. dairy	*Maize (silage)*	10.5	20	186	-	89	269	134	-	-	-	11.9	Y	S + M
	Faba bean	10.1	110	-	-	-	-	84	-	-	-	2.9	Y	-
	Winter wheat	10.8	180	75	-	33	79	86	-	-	-	4.7	N	S
	Summer wheat	3.6	170	-	-	-	-	84	-	-	-	3.3	Y	-
	Alfalfa	25.6	25	-	-	-	-	204	-	-	-	8.9	N	-
	Perm. Grass.	71.8	-	-	-	-	-	142	-	-	-	7.5	N	-
	Summer barley	3.4	160	-	-	-	-	84	-	-	-	3.5	Y	-
	Rye	7.8	140	75	-	33	79	86	-	-	-	3.6	N	S
	Potato	3.9	2500	118	-	56	190	103	-	-	-	22.6	Y	M
	Pea	2.8	90	-	-	-	-	84	-	-	-	3.6	Y	-
	Spelt	6.7	220	75	-	33	79	86	-	-	-	3.7	N	S
	Triticale	6.0	170	75	-	33	79	86	-	-	-	5.9	N	S
	Oat	7.5	140	-	-	-	-	84	-	-	-	3.8	Y	

[a] Values are expressed in kg of seed sown or, for tomato, number of seedlings.
[b] The amount of diesel used for drip irrigation was estimated to be 0.03 L m^{-3}.of water consumed, ased on an energy equivalence factor of 38.52 MJ L^{-1} of diesel (ecoinvent 3, market for diesel Europe without Switzerland), mean energy use of 1.0 MJ m^{-3} for drip irrigation (Qin et al., 2024), and a conversion factor of 0.9 kg diesel L^{-1}.
[c] Yields are expressed in dry matter or, for tomato and potato, fresh matter.

interpretation (Jolliet et al., 2015).

2.3.1. Goal and scope definition: system boundaries

LCA was performed using data from 2021 for DE and FR; 2022 for UK; and 2021 (tomato), 2022 (wheat), and 2019-2023 (silage maize) for IT. The system boundary extended from resource extraction to the farm gate and included emissions from all crop, forage, animal, and milk production (when present) (Fig. 1). Farm-level data on the use of electricity from the grid were lacking for the crop farms (IT and UK). Consequently, due to their focus on sustainable farming practices, and the UK farm's ability to generate enough electricity from solar panels to sell surplus electricity to the grid, the crop farms' use of electricity from the grid was excluded from the system boundaries.

2.3.2. Functional units

To reflect the farms' functions, we defined two functional units (FUs). The first FU represented land management, quantified as 1 ha of on-farm land occupied per year (ha.yr), and highlighted each farm's management intensity. We excluded off-farm land from this FU to focus on direct and indirect emissions of on-farm practices, which emphasized local consequences of management decisions.

The second FU represented production. We expressed this FU for the dairy farms as 1 kg of fat- and protein-corrected milk (FPCM), calculated as follows (IDF, 2015):

$$FPCM = M \times (0.1226 \times FC + 0.0776 \times PC + 0.2534) \times 1.03 \quad \text{[Eq. 1]}$$

where M is the amount of milk sold (L), FC is fat content (%), and PC is protein content (%).

To include only milk-related emissions for this FU, we excluded emissions from the production of animals (i.e., cull cows and calves sold), crops that were sold, and surplus forage that was stored.

For the crop farms, we sought a FU that represented total farm output, especially since the Italian farm produced both tomato and wheat. Accordingly, we chose 1 kg of all crop yields in dry matter (DM). To assess nutritional characteristics of crop products, we also calculated two additional FUs for crop farms: 1 kg of protein produced and 1 MJ of energy produced, based on contents of crude protein (% of DM) or metabolizable energy (MJ kg DM^{-1}), respectively, using French databases of feed composition (INRA-CIRAD-AFZ, 2017) or food composition (ANSES, 2020) (Table A1). Each farm was represented as a single process that aggregated all land uses. Each crop's annual DM production was calculated as the product of its yield (kg DM ha^{-1}) and area (ha).

2.3.3. Allocation of impacts among co-products

For crop production, we used economic allocation to attribute impacts to the primary product (e.g., grain) and a co-product (i.e., only straw). We addressed temporal and spatial variability in their prices by considering the mean price of durum wheat in the EU in 2021 (€350.00 t^{-1}) (EC, 2021b) and two means price of straw: €37.50 t^{-1} in Germany from 2010 to 2020 (excluding the peak price in the drought year of 2018) (Karras and Thrän, 2024) and €80.00 t^{-1} in the UK in 2021 (AHDB, 2024). This approach thus attributed 90% of impacts to primary products and 10% to co-products.

For grassland production (dairy farms only), we used allocation based on the DM mass of grazed grass and its potential co-products (i.e., grass silage, hay, and wrapped bales) in cattle diets throughout the year (Appendix B). For milk and cattle production, we used biophysical allocation of the AGRIBALYSE® v. 3.1 method (Koch and Salou, 2022) to attribute impacts of dairy cows to milk and calves (proportional to the

Table 2
Cattle and feeding-management data of the French and German dairy farms, with milk-production data expressed per ha of on-farm land used for cattle production (i.e., 122.8 and 132.4 ha, respectively). The stocking rate was calculated as the number of dairy cows (excluding heifers) divided by the area of grassland grazed.

Characteristic	Item	France	Germany
Breed		Holstein	Holstein
Mean herd composition (number)	Cows	124	91
	Cull cows	37	36
	Heifers	40	36
	Grazing calves	42	31
	Milk-fed calves	110	109
Mean age at first calving (months)		25.0	28.6
Mean daily diet per productive cow (kg dry matter day^{-1} head^{-1})	Maize silage	9	7
	Grass silage	1	3
	Grass grazed	6	0/6[a]
	Hay and straw	0.5	8/4[a]
	Total	17	18/20[a]
Concentrate feed fed (kg dry matter day^{-1} head^{-1})	Produced on-farm	0	3.6
	Produced off-farm	2.2	0.9
	Total	2.2	4.5
Grazing management	% of days per year outside	35	50
	Grassland grazed (ha)	77.5	14.0
	Stocking rate (cows ha^{-1})	1.6	6.5
Off-farm area used for cattle production (ha)	Multiple crops	9	11
On-farm cropland not used for cattle production (ha)	Multiple crops	8	38
Milk production (yr^{-1})	Per ha (L ha^{-1})	7635	5778
	Per cow (L cow^{-1})	7561	8407
Energy input (ha^{-1} yr^{-1})	Diesel (L)	147	146
	Electricity from the grid (kWh)	423	203

[a] amount of feed in winter/summer.

energy required to produce each co-product) and to cull cows (equal to those of renewal heifers).

2.3.4. Inventory analysis

We used the web-based software MEANS-InOut v. 4.4 to incorporate farm-level data on direct resource use (e.g., diesel, electricity from the grid, water, land) (or estimate some of it, if data were lacking), to estimate pollutant emissions (e.g., GHGs, ammonia, nitrate), and to create the life cycle inventories (LCIs), which list and quantify the flows of the system (Jolliet et al., 2015). Emission factors and modeling approaches of AGRIBALYSE® v. 3.1, which is embedded in MEANS-InOut, were applied to create LCIs for each crop field and life stage of the herd (i.e., calves, heifers, and dairy cows). Background processes (e.g., for production of inputs) from the ecoinvent v. 3.9 database (FitzGerald and Sonderegger, 2022) were used. Only fossil CO_2 emissions were included in the LCIs. Models of land-use change and SOC sequestration were not included, since we assumed no change in land use, and SOC dynamics were predicted separately using AMG (Ferchaud and Ramananjatovo, 2024).

2.3.5. Impact assessment

We used SimaPro® software (v. 9.5.0.1) (PRé Sustainability, Amersfoort, Netherlands) to aggregate the LCIs of crop production and, for dairy farms, cattle production, to estimate potential environmental impacts by classifying resource use and pollutant emissions into multiple impact categories (Jolliet et al., 2015). Potential environmental impacts were estimated using the Environmental Footprint 3.1 (adapted) method, as implemented in SimaPro. Although the study focused on the total climate change impact, the method's other 15 impact categories, as well as a normalized and weighted single score, were estimated for the FUs (Tables A6 and A7). The area of off-farm land required for each crop was calculated based on the land competition impact according to the CML non-baseline v. 3.07 method (Van Oers, 2016).

2.3.6. Contribution analysis

We performed contribution analysis to assess the relative contribution of each production process in the system to total impacts. Only processes that contributed more than 0.1% each were included in a specific process group; all other processes were classified as “other.” Following the approach of Mondière et al. (2024), the energy used to produce crops was aggregated into the process “direct energy use”.

2.4. Predicting dynamics of soil organic carbon and carbon sequestration

2.4.1. Simulation using AMG

We used AMG to simulate SOC dynamics at an annual time step (Clivot et al., 2019). AMG categorizes organic matter (OM) into two components: fresh OM, which comes from exogenous OM (EOM) (e.g.,

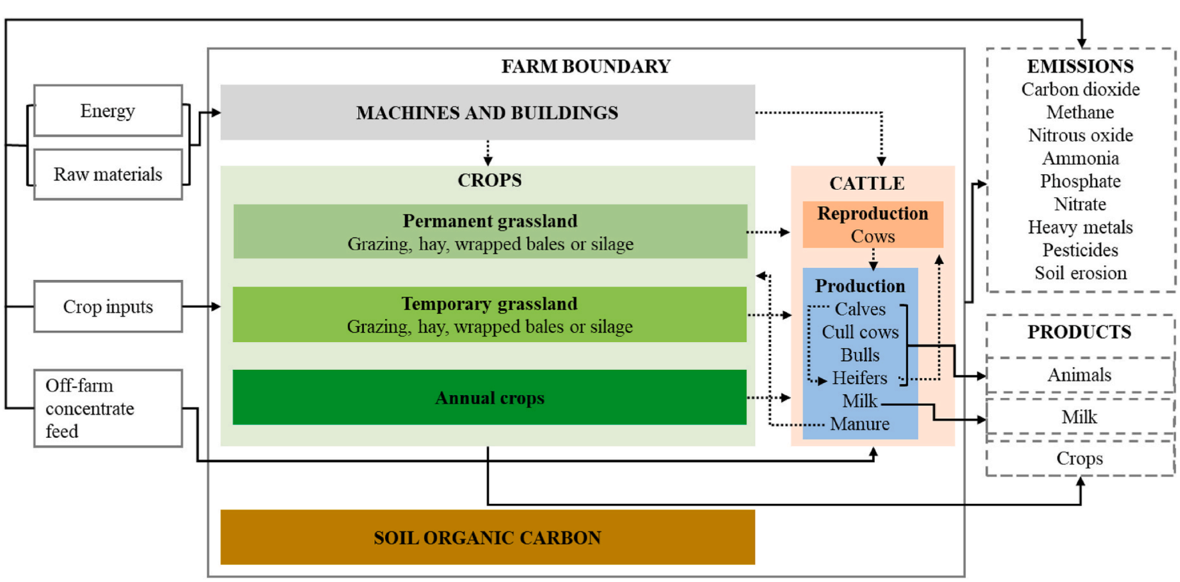

Fig. 1. Potential inputs, internal components, and outputs considered for the crop and dairy farms studied. Solid arrows are flows to or from the system, while dotted arrows are internal flows. Adapted from Mondière et al. (2024).

crop residues, animal waste), and soil OM, which consists of two pools: active C and stable C. AMG predicts total SOC stock (QC, t C ha $^{-1}$) using two main equations (Clivot et al., 2019):

$$QC = QC_S + QC_A \quad \text{[Eq. 2]}$$

$$\frac{dQC_A}{dt} = \sum_i m_i h_i - kQC_A \quad \text{[Eq. 3]}$$

where QC_A and QC_S are the active and stable C pools (t C ha^{-1}), respectively; m_i is the annual C input from EOM i (t C ha^{-1} yr^{-1}); h is its humification coefficient (the proportion of it incorporated into soil OM after 1 year); and k is the annual mineralization rate of the active C pool.

Due to limited soil data for the farms in the study, we assumed an initial total SOC stock of 51.6 t C ha^{-1} for cropland and 84.6 t C ha^{-1} for grassland, as recommended by the "4 per 1000" Initiative (Pellerin et al., 2019). We assumed no legacy effects of previous land-use change; thus, the initial SOC stock was assumed to be at equilibrium (steady state), and only the management practices in the scenarios influenced subsequent SOC dynamics. SOC dynamics on the dairy farms were calculated as a weighted mean of crop rotations and permanent grasslands (i.e., one crop rotation each for the UK and IT crop farms, three crop rotations and one permanent grassland for the FR dairy farm, and one crop rotation and one permanent grassland for the DE dairy farm) (Table A2). Using recommended values for AMG's parameters, we set the percentage of the total SOC stock in the stable C pool based on the management history of the field: 65% or 40% for fields with a long-term history of crops or grassland, respectively (Saffih-Hdadi and Mary, 2008). The stable C pool in AMG is assumed to resist mineralization completely during the simulation period (100 years) (Kanari et al., 2022), which is a conceptual simplification of SOC persistence in only two pools, since it can range from hours to millennia (Cécillon et al., 2021).

The mineralization rate in AMG is a function of mean annual air temperature, annual rainfall, annual potential evapotranspiration, soil clay content, and soil $CaCO_3$ content (Clivot et al., 2019), whose values we set in AMG based on measurements provided by the farm managers (Table 3). We assumed that each farm's climate characteristics (set to those observed in 2021) and crop yields remained constant during each simulation. We applied a correction factor to clay content to address the potential overestimation of clay content due to $CaCO_3$ content, since not doing so can overestimate C sequestration (Appendix C).

Parameters for simulating SOC dynamics for tomato were not available in the current version of AMG; thus, we identified an initial set of parameters for tomato based on a literature review (Whipps, 1987; Justes et al., 2009; Ronga et al., 2017; Uwamahoro et al., 2023), which was subsequently refined and validated by a specialist in AMG modeling (JC Mouny, Agro-Transfert, Ressources et Territoires, Estrées-Mons, France, pers. comm.). When simulating permanent grasslands, manure inputs during grazing were estimated using daily manure production per animal based on weight categories from Nennich et al. (2005), multiplied by the number of grazing days and number of animals in each category.

For each farm, the simulated active soil C pool increased or decreased at a decreasing rate over the simulation period (Fig. A1). For the eco-design scenarios, we adopted an amortization window of 20 years, which is the default Tier 1 transition period in IPCC guidelines (IPCC, 2006) to reach equilibrium of SOC stocks. We also used this 20-year window when calculating C sequestration in biomass for the rewilding mitigation action. Consequently, the mean annual contribution of a farm's practices to SOC dynamics equaled the active C pool after 20 simulated years minus the initial active C pool, divided by 20 years (Table A3). This mean annual C sequestration or depletion was converted to kg CO_2 eq. ha^{-1} yr^{-1} by dividing it by the C:CO_2 molar conversion factor (0.273). Each farm's net C balance equaled annual farm GHG emissions plus the mean annual C sequestration or depletion.

Table 3
Values of climate characteristics (for 2021) and soil properties used to initialize the AMG model to simulate the farms in Italy (IT), the United Kingdom (UK), France (FR), and Germany (DE).

Parameter	IT	UK	FR	DE
Mean annual air temperature (°C)	13.0	10.9	11.2	9.5
Annual rainfall (mm)	755	473	994	653
Annual potential evapotranspiration (mm)	655	655	600	573
Clay content (g kg^{-1} dry weight)[a]	320	201	198	284
$CaCO_3$ content (g kg^{-1} dry weight)	7.5	80.2[b]	2.1	1.5
pH	7.8	7.0	6.1	6.9
Carbon:nitrogen ratio	10.0	6.0	8.8	9.0

[a] Clay content after applying a correction factor to consider effects of $CaCO_3$ content on it.
[b] Estimated based on soils that were geographically proximate and had similar ranges of pH and clay content in the French BDAT database.

2.4.2. *Allocating predicted SOC dynamics to co-products of the dairy farms*

Predicting SOC dynamics for entire rotations made it more difficult to allocate them to co-products of the dairy farms as a function the proportion of crops and forage used in cattle diets. Therefore, we allocated SOC dynamics as a function of protein production. We first converted the liveweight of the calves sold and cull cows into total protein production using a conversion factor of 0.158 kg of total protein per kg liveweight (Laisse et al., 2018) (Table A4). Yields of crops and forage were converted into crude protein using the same French feed- and food-composition databases (Table A5). The mean protein content of milk was calculated using data from each dairy farm. Finally, we used the percentage of total protein produced on each dairy farm that was milk protein to determine how much of the farm's SOC dynamics to allocate to milk production when expressing impacts per kg FPCM.

2.5. *Uncertainty analysis*

Uncertainty analysis was performed to assess the influence of uncertainty in the initial SOC stock on AMG predictions of the active C pool after 20 years under the baseline scenario's practices and sequestration potential. To this end, the initial SOC stock of the baseline scenario was adjusted from −75% to +75% of its baseline value (in increments of 25 percentage points) for each crop rotation or area of permanent grassland on each of the four farms.

2.6. *Eco-design scenarios*

Based on the farm-level climate solutions catalogued by the ClieNFarm project (https://clienfarms.eu/solutions), we identified 11 eco-design actions: five to reduce GHG emissions and six to increase C sequestration (Table 4). To assess these actions, we developed two 20-year emission-reduction scenarios: productivity maintained (PM), in which productivity (i.e., total crop yield or milk production per farm) was maintained at 90% or more of its baseline value, and net zero (NZ), which focused on achieving net-zero GHG emissions. The business-as-usual practices of each farm served as the baseline. The C sequestration potential of each action was calculated as the active C pool of each farm after 20 years of implementing the action minus that after 20 years under the baseline.

In the PM scenario, we implemented up to eight actions per farm depending upon its characteristics: 1) replacing 20% of nitrogen (N) from inorganic fertilizers with N from manure, 2) converting fossil-fuel power for irrigation to solar power, 3) planting 100 m of hedges per ha (5 m wide), 4) reducing the area of land tilled by 50%, 5) adding cover crops, 6) leaving cereal straw on the soil and, for the dairy farms, 7) using a feed additive (3-NOP) to reduce enteric CH_4 emissions and 8) fertilizing permanent grasslands. In the NZ scenario, we removed the obligation to maintain productivity in order to reduce GHG emissions even further, which allowed for three actions: 9) replacing silage maize with temporary grassland on dairy farms, 10) using 20% less N fertilizer,

Table 4
Mitigation actions for two 20-year eco-design scenarios (S) (productivity maintained (PM) and net zero (NZ)), their type of effect (i.e., reduce greenhouse gas emissions or increase carbon sequestration (C seq.)), their assumed effect on productivity, the sources used for calculations, and the farm(s) on which each action was implemented (in Italy (IT), the United Kingdom (UK), France (FR), and Germany (DE)). See Appendix D for the actions' underlying assumptions and calculations.

S	Mitigation action	Effect type	Assumed effect on productivity	Calculation source (s)	Farm (s)
PM	Replacing 20% of N from inorganic fertilizers with N from manure	C seq.	Non-significant or positive	Effect type: this study. Effect on productivity: Kagan et al. (2024)	IT, UK, FR
	Converting fossil-fuel power for irrigation to solar power	Reduce emissions	Decrease as a function of the area of solar panels installed	Effect type: this study. Implementation GHGs: Todde et al. (2018)	IT
	Planting 100 m × 5 m of hedges per ha	C seq.	Decrease as a function of the area of hedges planted	Effect type: Drexler et al. (2021). Implementation GHGs: this study	IT, FR, DE
	Reducing the area of land tilled by 50%	Reduce emissions	Decrease in the short term	Effect type: this study. Effect on productivity: Pittelkow et al. (2015)	IT, FR, DE
	Establishing cover crops	C seq.	Non-significant or positive	Effect type: this study. Effect on productivity: Peng et al. (2024)	IT, UK, FR
	Leaving cereal straw on the soil	C seq.	Non-significant or positive	Effect type: this study. Effect on productivity: Liu et al. (2014)	IT, UK
	Using a feed additive to reduce enteric methane emissions	Reduce emissions	Non-significant or positive	Effect type: Kebreab et al. (2023) + this study. Effect on productivity and implementation GHGs: Alvarez-Hess et al. (2019) and (Kebreab and Feng, 2021)	FR
	Fertilizing permanent grassland	C seq.	Non-significant or positive	Effect type: this study. Effect on productivity: Shi et al. (2024) and Klumpp et al. (2007)	FR
NZ	Replacing silage maize with temporary grassland	Reduce emissions	Estimated decrease in milk yield: 14% for DE and 19% for FR	Both effects: this study	FR, DE
	Using 20% less inorganic N fertilizer	Reduce emissions	12% decrease	Effect type: this study. Effect on productivity: Pacifico et al. (2024)	IT, FR
	Rewilding the area of land needed to achieve net zero	C seq.	Decrease as a function of the area rewilded	Effect type: Mondière et al. (2024)	IT, FR, DE

and as a final action, 11) rewilding the area of each farm's land needed to reach net zero.

The potential impact of each action on productivity was estimated based on the literature and the land area required for implementation, assuming that the percentage reduction in farm-level productivity, resource use, and pollutant emissions equaled the percentage of land area no longer used for production. Additionally, effects of changing dairy cow diets on milk production were predicted using Dairy-8 software (v. 8. R2024.05.05) (NASEM, 2024) (Table 4). MEANS-InOut and SimaPro were also used to calculate reductions in emissions for the eco-design scenarios. When applicable, additional GHG emissions related to implementing and maintaining each action (hereafter, "implementation GHGs") were also estimated to assess their contribution to the scenario. To quantify how much of an action's mitigation potential was lost by implementing it, we calculated its implementation GHGs as a percentage of its mitigation potential. See Appendix D for the actions' underlying assumptions and calculations. The total contribution of each action to reducing a farm's net C balance equaled the action's implementation GHGs plus its mitigation potential (i.e., GHG reductions or SOC sequestration). Effects of the actions were assumed to be additive, with no interactions.

3. Results

3.1. Farm performance and indirect emissions

The farms represented distinct crop and dairy production systems. For the crop farms, the IT farm's high fertilizer inputs were typical of intensive farming, and its yields exceeded national means (FAO, 2024). In contrast, the UK farm's productivity aligned with national means, though its rapeseed yields (Table 1) were slightly lower (FAO, 2024), likely due to its focus on sustainability over maximum output. For the dairy farms, the conventional FR farm exceeded both national and EU mean crop yields and the national mean milk yield (Eurostat, 2024; FAO, 2024), while the organic DE farm exceeded the EU mean milk yield, perhaps due to its ability to produce large amounts of forage (Bang et al., 2024). However, neither the FR nor DE dairy farm was self-sufficient in feed: off-farm concentrate feed represented 13% and 4% of the mean daily diet of productive cows, respectively (Table 2). The FR farm imported conventional rapeseed meal, which required 8 ha of external land, while the DE farm imported organic winter wheat and faba beans, which required 11 ha of external land.

The indirect emissions highlighted distinct externalities associated with each farm. For example, the IT farm's indirect emissions of phosphate, CO_2, and CH_4 per ha of on-farm land occupied per year were 2, 6, and 12 times as high, respectively, as those of the UK farm (Table 5). On the FR farm, indirect emissions of N_2O, CH_4, and CO_2 per ha of on-farm land occupied per year were 1.5, 1.5, and 2.7 times as high, respectively, as those of the DE farm (Table 5).

3.2. Environmental impacts in the baseline scenario

Compared to the IT farm, the UK farm had higher environmental impacts regardless of the FU only for the categories of freshwater ecotoxicity (due to using nearly twice the amount of pesticides), marine eutrophication, and land use, which resulted in a lower overall single score (Table A6). Compared to the FR farm, the DE farm had higher impacts per ha of on-farm land only for land use, and per kg FPCM only for eutrophication (marine and freshwater), land use, and photochemical ozone formation, which resulted in a lower overall single score (Table A7).

The climate change impact per ha of on-farm land varied greatly among the IT, UK, FR, and DE farms: 5570, 2505, 10,208, and 6274 kg CO_2e ha^{-1}, respectively (Fig. 2, Table A8). The climate change impact per kg of product also varied greatly: 0.8 and 0.4 kg CO_2e kg DM^{-1} for the IT and UK crop farms, respectively, and 1.06 and 0.88 kg CO_2e kg

Table 5
Measured inputs, estimated direct and indirect pollutant emissions, and percentages of direct and indirect greenhouse gas (GHG) emissions for the farms in Italy (IT), the United Kingdom (UK), France (FR), and Germany (DE). Inputs and emissions are expressed per ha of on-farm land occupied per year.

Category	Element	Unit	IT	UK	FR	DE
Inputs	Electricity from the grid	kWh	-[a]	-[a]	466	268
	Natural gas	m^3	547	0	0	0
	Diesel	L	168	41	124	130
	Nitrogen in organic fertilizers	kg	0	0	131	102
	Nitrogen in inorganic fertilizers	kg	223	122	62	0
	Phosphate in inorganic fertilizers	kg	108	92	87	0
	Herbicide active ingredients	kg	3.0	5.6	1.1	0
	Irrigation water	m^3	5607	0	0	0
	Off-farm concentrate feed[b]	kg	0	0	597	176
Direct pollutant emissions	Nitrate (NO_3)	kg	201	195	178	135
	Phosphate (PO_4)	kg	0.2	0.2	0.6	0.8
	Ammonia (NH_3)	kg	10	5	47	23
	Methane (CH_4)	kg	0	0	257	160
	Carbon dioxide (CO_2)	kg	542	919	863	977
	Nitrous oxide (N_2O)	kg	3.4	3.2	4.3	1.7
Indirect pollutant emissions	Nitrate (NO_3)	kg	5	16	31	61
	Phosphate (PO_4)	kg	1.2	0.6	0.9	0.6
	Ammonia (NH_3)	kg	1.4	1.0	1.6	3.1
	Methane (CH_4)	kg	12	1.0	2.7	2.0
	Carbon dioxide (CO_2)	kg	3594	556	878	324
	Nitrous oxide (N_2O)	kg	0.6	0.7	1.2	0.8
GHG emissions	Direct	%	13	62	56	78
	Indirect	%	87	38	44	22

[a] Use of electricity from the grid was excluded from the system boundaries for the two crop farms because both focused on sustainable farming practices and the UK farm could generate enough electricity from solar panels to sell surplus electricity to the grid.
[b] FR: barley, faba beans, and rapeseed meal; DE: wheat and faba beans.

FPCM^{-1} for the FR and DE dairy farms, respectively (Fig. 3, Table A8). The climate change impact of the crop farms was driven mainly by direct CO_2 emissions from urea/lime application and N_2O emissions from denitrification and decomposition in the soil, along with indirect emissions from processes related to fertilizers and seeds/seedlings. The climate change impact of the FR and DE dairy farms was driven mainly by enteric CH_4 emissions, which, excluding SOC dynamics, contributed 45-46% and 51-53%, respectively, for both FUs, followed by manure management (25-27% and 19-20%, respectively), and direct energy use (11% and 17-18%, respectively) (Figs. 2 and 3, Table A8).

3.3. Uncertainty analysis

On average, the initial SOC stock influenced predicted C sequestration potential much more than it influenced the predicted final active C pool (and in the opposite direction). For example, for crop rotations and permanent grassland, a ±25% change in the initial SOC stock changed the former (inversely) by a mean of ±48% and ±78%, respectively (Fig. A2a), and the latter (directly) by a mean of ±6% and ±12%, respectively (Fig. A2b). Additionally, if initial SOC stocks were 75% lower than assumed, baseline practices would be predicted to increase the final active C pool of all farms, but if they were 75% higher than assumed, the UK, FR, and IT farms would lose 1.7%, 2.7%, and 128% of the active C pool, respectively, with mean losses of 27% in crop rotations and 70% in permanent grassland.

The soil data available for crop fields on the IT, UK, and DE farms (2, 5, and 1 field, respectively) revealed mean SOC stocks that were 25%, 39%, and 7% higher, respectively, than the initial SOC stock assumed in the study (51.6 t C ha^{-1} y^{-1}) and field-specific SOC stocks that varied moderately (coefficients of variation of 16%, 19%, and not defined, respectively).

3.4. Predicting carbon sequestration with the AMG model

Over the 20-year simulations, AMG predicted diverging trends in the active C pools of the IT and UK crop farms (initially 18.1 t C ha^{-1}) due to differences in their management practices. On the IT farm, which tilled the soil, exported most crop residues, did not plant cover crops, and applied compost of municipal solid waste, the active C pool decreased by 5.8 t C ha^{-1}. In contrast, on the UK farm, which did not till the soil, planted cover crops, and returned most crop residues to the soil, the active C pool increased by 4.8 t C ha^{-1}. Thus, the mean annual C sequestration rate was −0.29 and 0.24 t C ha^{-1} on the IT and UK farms, respectively, which was equivalent to GHG emissions of 1060 kg CO_2e ha^{-1} yr^{-1} on the IT farm and GHG mitigation of 880 kg CO_2e ha^{-1} yr^{-1} on the UK farm (Fig. 2, Table A8).

On the FR farm, C sequestration dynamics differed among the three

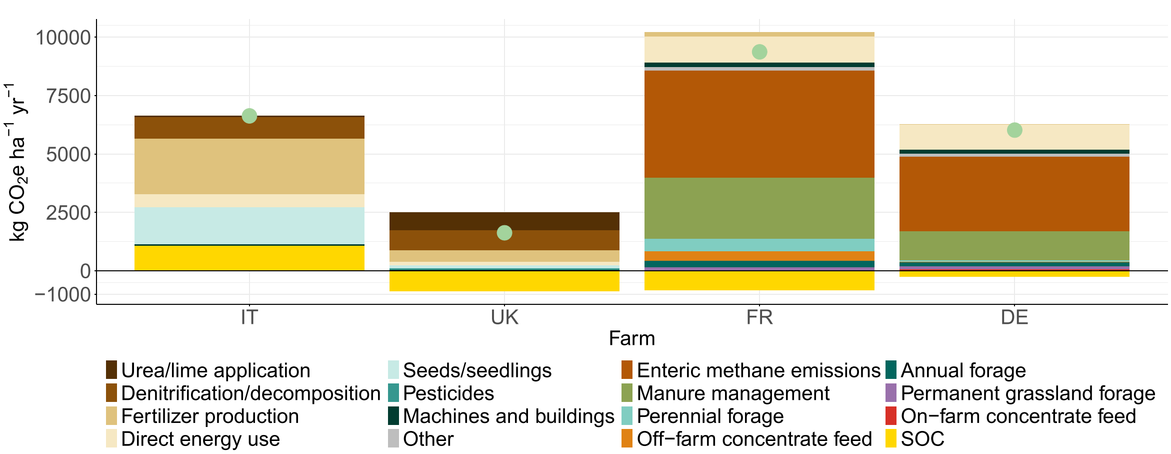

Fig. 2. Contribution of production processes to the climate change impact expressed in kg CO_2e per ha of on-farm land occupied per year for the crop farms in the United Kingdom (UK) and Italy (IT) and the dairy farms in Germany (DE) and France (FR). Soil organic carbon (SOC) equals the negative of the mean annual decrease (carbon depletion) or increase (carbon sequestration) in SOC stock predicted by a 20-year simulation of the AMG model. Green dots indicate the net impact, which equals greenhouse gas emissions minus the annual change in SOC stock. "Other" represents processes that contributed less than 0.1% each. See Table A3 for predictions of SOC sequestration at the farm level.

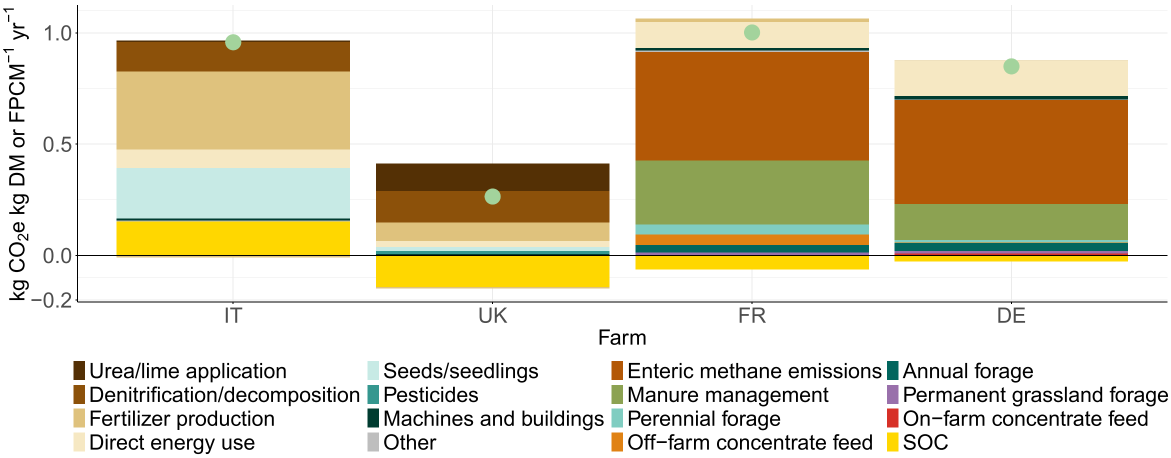

Fig. 3. Contribution of production processes to the climate change impact expressed in kg CO_2e per kg of crop dry matter (DM) yield for the crop farms in the United Kingdom (UK) and Italy (IT) or per kg of fat and protein-corrected milk (FPCM) for the dairy farms in Germany (DE) and France (FR). Soil organic carbon (SOC) equals the negative of the mean annual increase (carbon sequestration) in SOC stock predicted by a 20-year simulation of the AMG model. Green dots indicate the net impact, which equals greenhouse gas emissions minus the annual increase in SOC stock. "Other" represents processes that contributed less than 0.1% each. See Table A3 for predictions of SOC sequestration at the farm level.

crop rotations and the permanent grassland. After 20 years of conventional practices, which included organic fertilization of silage maize and temporary grassland, tillage, and returning cover crop residues to the soil (except for cereal straw), the active C pool in the three crop rotations (initially 18.1 t C ha^{-1}) increased by 4.4, 9.4, and 8.6 t C ha^{-1}, respectively, while that in permanent grassland (initially 50.8 t C ha^{-1}) decreased by 7.3 t C ha^{-1}. At the farm level, this increased the active C pool by 4.6 t C ha^{-1}, which equaled a mean annual C sequestration rate of 0.23 t C ha^{-1} yr^{-1}, which was equivalent to GHG mitigation of 837 kg CO_2e ha^{-1} yr^{-1} (Fig. 2, Table A8). Overall, milk contributed 57% of the climate change impact per kg of protein produced, which resulted in allocating 0.06 kg CO_2e per kg FPCM of predicted SOC sequestration to milk production.

On the DE farm, 20 years of organic practices, which included organic fertilization, tillage, cover cropping, and returning faba bean and cover crop residues to the soil, increased the active C pool in the crop rotation by 5.7 t C ha^{-1} (Table A3). In contrast, despite its permanent grassland being fertilized with cattle slurry and receiving cattle excreta during grazing, its active C pool decreased by 4.5 t C ha^{-1}. At the farm level, this increased the active C pool by 1.4 t C ha^{-1}, which equaled a mean annual C sequestration rate of 0.069 t C ha^{-1} yr^{-1}, equivalent to GHG mitigation of 253 kg CO_2e ha^{-1} yr^{-1} (Fig. 2). Overall, milk contributed 56% of the climate change impact per kg of protein produced, which resulted in allocating 0.03 kg CO_2e kg $FPCM^{-1}$ of predicted SOC sequestration to milk production.

3.5. Eco-design scenarios and net-zero farming

None of the farms in the study operated at net-zero GHG emissions in the baseline scenario, whether per ha or per kg of product (Figs. 2 and 3). Although soils on the UK, DE, and FR farms acted as C sinks, C sequestration mitigated only 35%, 6-8%, or 3-4% of the climate change impact, respectively, for the two FUs (Figs. 2 and 3). In contrast, soils on the IT farm acted as a C source, which increased the farm's climate change impact by 19% per ha and per kg DM (Figs. 2 and 3).

For the IT farm, six mitigation actions were modeled in the PM scenario: replacing 20% of inorganic N fertilizers with N from manure, converting fossil-fuel power for irrigation to solar power, planting 100 m of hedges per ha, reducing the area of land tilled by 50%, establishing cover crops, and leaving cereal straw on the soil. Additional mitigation actions in the NZ scenario were to reduce N fertilizer use by 20%, and, to achieve net zero, rewild 25 ha (33%) of the farm. The six mitigation actions in the PM scenario were estimated to reduce the farm's baseline net C balance by 18%, 11%, 14%, 2%, 1%, and 4%, respectively (total: 49%) (Table 6). The two mitigation actions in the NZ scenario reduced it by an additional 17% and 34%, respectively (Table 6).

The UK farm was the only farm that achieved net-zero GHG emissions in the PM scenario, in which three mitigation actions were modeled: replacing 20% of inorganic N fertilizers with N from manure, establishing cover crops, and leaving cereal straw on the soil. These three actions were estimated to reduce the farm's baseline net C balance by 92%, 21%, and 6%, respectively (total: 119%) (Table 6). The reduction greater than 100% indicates that the UK farm changed from a net C source to a net C sink.

For the FR farm, six mitigation actions were modeled in the PM scenario: replacing 20% of inorganic N fertilizers with N from manure, planting 100 m of hedges per ha, reducing the area of land tilled by 50%, establishing cover crops, fertilizing permanent grassland with slurry, and using 3-NOP to reduce enteric CH_4 emissions. Additional mitigation actions in the NZ scenario were to replace silage maize with temporary grassland and, to achieve net zero, rewild 66 ha (51%) of the farm. The six mitigation actions in the PM scenario were estimated to reduce the farm's baseline net C balance by 12%, 10%, 1%, 0.5%, 1%, and 15%, respectively (total: 38.5%) (Table 6). The two mitigation actions in the NZ scenario reduced it by an additional 12% and 50%, respectively (Table 6).

For the DE farm, two mitigation actions were modeled in the PM scenario: planting 100 m of hedges per ha and reducing the area of land tilled by 50%. Additional mitigation actions in the NZ scenario were to replace silage maize with temporary grassland and, to achieve net zero, rewild 81 ha (48%) of the farm. The two mitigation actions in the PM scenario were estimated to reduce the farm's baseline net C balance by 15.1% and 0.4%, respectively (total: 15.5%) (Table 6). The two mitigation actions in the NZ scenario reduced it by an additional 16% and 68%, respectively (Table 6).

4. Discussion

4.1. Mechanisms for and trade-offs in farm-level GHG mitigation

The effectiveness of mitigation actions in the study depended greatly on farm characteristics. On the UK crop farm, for example, relatively simple changes, such as replacing 20% of inorganic N fertilizers with manure, were nearly sufficient to achieve net zero. As in other LCA

Table 6
Contribution of sequential mitigation actions in two 20-year eco-design scenarios (S) – productivity maintained (PM) and net zero (NZ) – to decreasing greenhouse gas (GHG) emissions of the baseline (business as usual (BAU)) scenario of the four farms (F) in the study (in Italy (IT), the United Kingdom (UK), France (FR), and Germany (DE)). See Table 4 for descriptions of the actions and Appendix D for their underlying assumptions and calculations. IGHG (implementation GHGs): estimated increase in GHG emissions or reduction in SOC sequestration of implementing an action, MP (mitigation potential): estimated reduction in GHG emissions or increase in SOC sequestration caused by an action, TC (total contribution): IGHG + MP, Net: the net carbon balance (annual farm GHG emissions +mean annual change in SOC stock) that remained after implementing the action, MPL% (MP lost): IGHG as a percentage of MP, TC%: the percentage by which the action's TC decreased the baseline Net, CM%: the cumulative percentage of mitigation achieved by the current and previous actions, with negative changes greater than −100% indicating that the farm became a carbon sink.

F	S	Mitigation action	kg CO_2e ha^{-1} yr^{-1}				MPL%	TC%	CM%
			IGHG	MP	TC	Net			
IT	BAU	Net carbon balance after 20 years of BAU	-	-	-	6630	-	-	-
	PM	Replacing 20% of mineral N fertilizer with manure	834	−2032	−1198	5432	−41.0	−18.1	-
	PM	Converting fossil-fuel power for irrigation to solar power	399	−1136	−737	4695	−35.1	−11.1	-
	PM	Planting 100 m of hedges per ha	45	−953	−908	3787	−4.7	−13.7	-
	PM	Reducing the area of land tilled by 50%	-	−139	−139	3648	-	−2.1	-
	PM	Establishing cover crops	52	−96	−44	3604	−54.2	−0.7	-
	PM	Leaving cereal straw on the soil	2	−239	−237	3367	−0.1	−3.6	−49
	NZ	Using 20% less nitrogen fertilizer	233	−1352	−1119	2248	−17.2	−16.9	−66
	NZ	Rewilding the area of land needed to achieve net zero	-	−2248	−2248	0	-	−33.9	−100
UK	BAU	Net carbon balance after 20 years of BAU	-	-	-	1620	-	-	-
	PM	Replacing 20% of mineral N fertilizer with manure	465	−1955	−1490	130	−23.8	−92.0	-
	PM	Establishing cover crops	58	−404	−346	−216	−14.4	−21.4	-
	PM	Leaving cereal straw on the soil	-	−97	−97	−313	-	−6.0	−119
FR	BAU	Net carbon balance after 20 years of BAU	-	-	-	9371	-	-	-
	PM	Replacing 20% of mineral N fertilizer with manure	251	−1356	−1105	8266	−18.5	−11.8	-
	PM	Planting 100 m of hedges per ha	45	−953	−908	7358	−4.7	−9.7	-
	PM	Reducing the area of land tilled by 50%	-	−68	−68	7290	-	−0.7	-
	PM	Establishing cover crops	12	−58	−46	7244	−20.7	−0.5	-
	PM	Fertilizing permanent grasslands	164	−266	−102	7142	−61.7	−1.1	-
	PM	Using a feed additive to reduce enteric methane emissions	8	−1385	−1377	5765	−0.6	−14.7	−38.5
	NZ	Replacing silage maize with temporary grassland	80	−1200	−1120	4645	−6.7	−12.0	−50.4
	NZ	Rewilding the area of land needed to achieve net zero	-	−4645	−4645	0	-	−49.6	−100
DE	BAU	Net carbon balance after 20 years of BAU	-	-	-	6021	-	-	-
	PM	Planting 100 m of hedges per ha	45	−953	−908	5113	−4.7	−15.1	-
	PM	Reducing the area of land tilled by 50%	-	−26	−26	5087	-	−0.4	−16
	NZ	Replacing silage maize with temporary grassland	8	−977	−969	4118	−0.8	−16.1	−32
	NZ	Rewilding the area of land needed to achieve net zero	-	−4118	−4118	0	-	−68.4	−100

studies, indirect emissions from farm inputs contributed greatly to the environmental impacts, especially for the more intensive systems. The four farms represented crop and dairy systems with varying agricultural contexts, production intensities, and sustainability approaches. The UK crop farm prioritized sustainability, the IT crop farm prioritized maximum productivity in a sustainability framework, and the dairy farms followed either conventional (FR) or organic (DE) models. These contrasting strategies led to different distributions of environmental impacts per ha and per kg of product.

Despite the UK farm's relatively low impacts in nearly all impact categories per ha of on-farm land, it had the highest ecotoxicity impact for both FUs. This raises questions about whether its crop-management practices are consistent with its long-term focus on environmental sustainability, including potential effects on essential processes such as plant-fungi symbioses and nutrient cycling (Edlinger et al., 2022). However, because it provided data only for a single year, no temporal trends were available. Most farm-level data for the LCA came from 2021 to 2022. While the regions of all four farms tended to have near-average annual temperatures and precipitation in 2021 (C3S, 2021) (compared to 1991-2020 averages), they had above-average annual temperatures and below-average annual precipitation in 2022 (C3S, 2022). Management practices and resulting environmental impacts can vary among years due to differences in weather, yields, irrigation, and pest pressure. For example, the high pesticide use reported on the UK farm for 2022 may have reflected an unusually severe pest or disease outbreak in winter wheat. Additional multiyear studies would be necessary to generalize the effects of the mitigation actions assessed.

Unlike the UK farm, the IT farm's high productivity came with high GHG emissions per ha. Indirect CH_4 and CO_2 emissions associated with producing inorganic fertilizers and growing seedlings in greenhouses were nine and three times as high per ha, respectively, as those of the UK farm. These results agree with studies that warn of blind spots in emissions accounting, particularly for non-CO_2 gases such as CH_4 and N_2O or indirect impacts such as land-use change and nutrient depletion (Amelung et al., 2020; Guenet et al., 2021; Khalil et al., 2024).

Since sustainability is inherently multi-dimensional, translating it into mitigation strategies requires a systems approach that captures trade-offs among these dimensions. While optimizing productivity remains essential to meet global food demands, it should not increase overall environmental impacts. The results indicate that although farms with low GHG emissions per ha may not be sufficiently generalizable or productive to be adopted widely, they provide valuable insights into practices that can reduce emissions or increase C sequestration per ha. For example, even if actual SOC stocks were 75% higher than those assumed, the UK farm's baseline practices would nearly maintain the active C pool, whereas the other farms would lose even more C. Indeed, the measured SOC stocks were higher than those assumed when initializing the AMG model for the few fields assessed. Since SOC is a key indicator of soil health (Bünemann et al., 2018), these results highlight the relative sustainability of the UK farm's baseline practices and the importance of estimating SOC accurately. Due to the limited availability of measured SOC, we standardized the initial SOC stock for all farms, which strengthened the ability to isolate effects of mitigation actions on SOC dynamics. Nonetheless, field validation remains crucial to refine model equations to predict site-specific C sequestration more accurately. In contrast, highly productive farms that appear efficient per unit of product may require large amounts of farm inputs, but farms with low GHG emissions per ha may entail land-use opportunity costs, since producing less food per ha decreases the land available for other mitigation actions (Spencer et al., 2025); thus, high-productivity systems with lower SOC stocks may remain more sustainable over larger areas when land-use efficiency is considered.

4.2. Modeling SOC contributions to mitigation of farm-level emissions

Even when on-farm practices increased predicted SOC sequestration, SOC sequestration alone was insufficient to offset GHG emissions. AMG predictions highlighted the crucial role of fertilization with EOM in maintaining and increasing soil SOC stocks, which is consistent with results of other studies (Gross and Glaser, 2021).

The large contribution of fertilization with cattle manure indicates that it needs to be estimated carefully. AMG's humification coefficients come from Levavasseur et al. (2020), who derived them from changes in SOC stocks in experiments in four European countries. Differences in the humification coefficients of cattle manure (range: 0.44-0.99) were attributed to differences in feed, bedding, and the duration and type of manure storage. Humification coefficients are influenced by the quality of EOM (Berti et al., 2016), soil properties, and climate characteristics (Levavasseur et al., 2020). Accurately representing the quality of EOM in SOC models is a known challenge (Mondini et al., 2017). AMG represents the C content and humification coefficient for several types of EOM, which makes it more useful than other models that predict SOC dynamics and helps stakeholders use it to assess management of EOM. Nonetheless, to predict the sequestration potential of EOM inputs more accurately, site-specific data on the chemical composition of EOM and soil properties should be used.

On dairy farms, the proportion of humified C in EOM can be increased by composting manure or separating the solid fraction of slurry, the latter of which increases the C content in the solid fraction, thereby increasing its contribution to SOC sequestration (Zhang et al., 2022). Since local manure surpluses pose environmental challenges (Sadeghpour and Afshar, 2024), such processing technologies can support more circular nutrient flows. Emerging options such as producing REcovered Nitrogen from manURE (RENURE) materials (Vingerhoets et al., 2025) further increase the efficiency of using manure-derived nutrients on other farms that need them and help address spatial nutrient imbalances. Since replacing 20% of inorganic N fertilizers with N from manure emerged as one of the actions with the most impact for all farms in the study, manure exchanges within a region could be a viable strategy, particularly for farms with few or no livestock.

The study also highlighted the importance of using SOC modeling to estimate effects of mitigation actions on SOC dynamics, as well as of using LCA to estimate their implementation GHGs, since ignoring the implementation GHGs of replacing 20% of mineral N fertilizer with manure on the UK farm, for example, would have overestimated the action's actual (i.e., net) mitigation potential by 24% (Table 6). It is therefore imperative to identify and prioritize actions that increase C inputs while maintaining or reducing net GHG emissions.

4.3. Limitations and data gaps of predicting SOC dynamics

Despite its utility, modeling SOC has limitations, and C-sequestration predictions should be interpreted with caution, especially for organic systems and grasslands. Like many SOC models, AMG is parameterized for conventional agricultural systems and may not predict plant biomass in organic systems as accurately due to how it represents plant structure, such as the shoot-to-root ratio (Vlachostergios and Roupakias, 2008). Since AMG uses these ratios to calculate C inputs, it may underpredict belowground biomass and thus C sequestration. Parameterizing AMG with validated shoot-to-root ratios for organic systems would likely yield more accurate predictions.

AMG also predicted that SOC stocks of the permanent grassland of both dairy farms decreased. While this prediction contrasts with observations of certain studies (Conant et al., 2017; Poeplau, 2021; Dămătîrcă et al., 2025), it agrees with other studies that found that intensive grazing can increase or decrease SOC stocks depending on the management practices (Zeeman et al., 2010; Abdalla et al., 2018; Chang et al., 2021; Simmons et al., 2026). The net C balance, which determines whether systems act as net C sources or sinks over the long term, and C sequestration potential of grasslands are influenced by the initial SOC stock and management practices, which influence lateral C fluxes (i.e., imported in EOM and exported in harvested or grazed biomass) (Lloyd et al., 2025). Intensive livestock grazing can decrease plant cover, species diversity, and overall productivity, thereby reducing root-derived C inputs and microbial SOC formation, while increasing microbial turnover and erosion (Zhou et al., 2017; Bai and Cotrufo, 2022). These potential negative effects of intensive livestock grazing on grassland SOC stocks and the high contribution of enteric CH_4 to GHG emissions suggest that reducing livestock numbers would reduce C losses and GHG emissions, thereby contributing to net-zero targets. In line with these considerations, an international interdisciplinary commission has recommended that consumption of animal products be reduced in developed countries to promote sustainable and healthy food systems, but these recommendations have not yet been widely implemented (Rockström et al., 2025).

Additionally, AMG represents only some of the effects of grazing and C-specific factors in grasslands. While it does represent grass yield and C inputs from cattle excreta during grazing, it does not explicitly represent multi-species grasslands. Thus, since both dairy farms included legumes, which increase SOC stocks (Conant et al., 2017), in their grassland mixtures, AMG may have underpredicted SOC sequestration in their grasslands. Future modeling studies of SOC stocks could increase predictive accuracy by including more detailed data on grassland composition, species diversity, grazing and excretion patterns, and biomass production. Thus, we emphasize the need for more data and more accurate model parameterization for alternative agricultural systems, especially since these systems are increasingly promoted for their potential to reduce GHG emissions and pesticide use and favor biodiversity.

4.4. Eco-design as a planning tool: strengths and limitations

The uncertainty analysis highlighted the strong influence of the initial SOC stock on predicted C sequestration, which was consistent with predictions of other SOC models (Post et al., 2008; Diel and Franko, 2020). While absolute predictions of SOC stocks after 20 years were sensitive to this baseline assumption, relative changes in predicted SOC stocks among the farms and scenarios could be compared with more confidence, since all of them were subject to the same assumption, as demonstrated by Zhou et al. (2023). These results support using scenario modeling to guide development of eco-design plans and policies, particularly to identify promising mitigation strategies. However, the current degree of model uncertainty limits its applicability for guiding development of C payment plans or offsetting frameworks, which require more accurate absolute predictions of C sequestration. To increase the robustness of model calibration and the confidence in absolute predictions, sensitivity analyses that identify the most influential parameters could help prioritize data collection in the field.

In the 20-year simulations, AMG did not represent temporal feedback loops related to changes in the climate, yields, or nutrient cycling, such as the observation that, compared to applying inorganic N fertilizers, repeated EOM applications can increase topsoil N stocks and N-use efficiency over time (Song et al., 2022; Oberson et al., 2024). These soil N dynamics introduce uncertainty into fertilization plans and emission estimates, which increases the complexity of simulating nutrient availability and environmental impacts. In particular, low short-term availability of organic N can increase mineralization in the soil years later, which can increase the risk of nitrate leaching (Chalhoub et al., 2013). Additionally, models that do not represent legacy effects of previous N applications accurately may underpredict N_2O emissions (Qian et al., 2025). More dynamic approaches are needed to better predict nitrate leaching and N_2O emissions.

In addition to these dynamics, interactions among management practices or mitigation actions are complex and need to be assessed empirically. For example, we did not model effects of cover crops on the yields of main crops, although studies indicate that they can be large (Wittwer and van der Heijden, 2020). Legume cover crops can increase subsequent maize yields, while non-legume cover crops can have no or even negative effects on yields (Smit et al., 2019). Similarly, applying organic and inorganic fertilizers together often synergistically increases yields and nutrient retention (Song et al., 2022). Recent studies have found that farms that use multiple diversification strategies tend to achieve more "win-win" outcomes (Rasmussen et al., 2024). Future research should focus on assessing these interactive effects under field conditions to ensure more reliable implementation of mitigation strategies that can be adopted more widely.

4.5. Feasibility and limits of achieving net zero GHG emissions at the farm level

Achieving net zero in agriculture is complex. Although SOC sequestration is widely promoted (Lal et al., 2021), results of the present study indicate that it cannot deliver net zero on its own when farm productivity must be maintained. The crop farms studied reduced GHG emissions greatly using lower-impact practices, but achieving net zero would require more transformative strategies, such as planting hedges, or others that require more investment, such as solar-powered irrigation. Transitioning to renewable energy will be a cornerstone of sustainable systems in all sectors (Gielen et al., 2019). Nonetheless, doing so has high environmental and economic costs (Table D1), which highlights the need to increase its effectiveness and lifecycle performance. Governments can play a key role by promoting green technologies in agriculture through policies (Chen et al., 2024). Using solar power in agriculture could enhance ecosystem services, support biodiversity (Semeraro et al., 2022; Williams et al., 2023), and increase farmers' self-sufficiency in energy, particularly if implemented through subsidies or cooperative plans (Brudermann et al., 2013; Weselek et al., 2019). On the IT farm, converting irrigation to solar power was used as an illustrative mitigation action. Since renewable-energy prices have decreased greatly in the past decade, purchasing renewable electricity from the grid, where available, provides an alternative to high on-farm investment costs (Vatankhah Ghadim et al., 2025). Other renewable energy sources – such as geothermal and wind power (Majeed et al., 2023), biomethane grid injection (Pasini et al., 2019), and collective biogas plants for multiple small farms (Burg et al., 2021) – also represent cost-effective options for reducing a farm's environmental impacts and, in some cases, generating additional revenue.

Achieving net zero posed an even greater challenge for the dairy farms studied, which required setting aside more than 50% of their area for land-based C sinks, such as rewilded land, which is consistent with predictions for other ruminant systems (McNicol et al., 2024). Additionally, although setting the duration of mitigation actions is critical for defining the transparency and feasibility of C sequestration in agriculture (Dynarski et al., 2020), the 20-year window that we adopted could be changed. Encouraging farmers to commit to performing mitigation actions during the entire duration would require strong regulatory or financial incentives, since such commitments limit farmers' operational flexibility (White, 2022).

Moreover, the permanence of SOC sequestration remains a major question. The SOC stock is a dynamic balance between inputs and decomposition, and residence times of C span decades to centuries (Don et al., 2024), whereas the climate effects of emitted GHGs persist for millennia. This mismatch restricts the long-term compensatory value of SOC sequestration (Arcusa and Lackner, 2025). More durable C-storage options may therefore be needed alongside SOC-based measures. Under the EU Carbon Removals and Carbon Farming Certification Framework (CRCF) (EU, 2024), permanent C removals are defined as practices that store C for several centuries through geological storage, C mineralization, and long-lasting C-bound products. Within this framework, biochar is a relevant option for agricultural systems since it can store C in a stable form for centuries. Its mitigation potential, however, depends on the proportion of stable C in the soil, soil properties, management practices, how long it has been in the soil, and the potential decomposition rate (Field et al., 2013; Schmidt et al., 2019; Maenhout et al., 2024).

These results reinforce the idea that achieving net zero at the farm level, particularly for livestock systems, is highly ambitious and potentially infeasible without structural and policy support. Research suggests that achieving net zero in agriculture is more feasible at the regional or sectoral level, at which mitigation actions can be shared and then adjusted to local conditions (ADEME, 2021; Reijnders, 2023). For example, surplus nutrients in one region can be distributed to regions that lack them, which increases circularity (Wei et al., 2025). Similarly, when farms have already implemented key mitigation actions, remaining emissions can be offset through collaborative or compensation mechanisms (Axelsson et al., 2024). Sectoral level "insetting" (i.e., mitigation actions within a value chain) is also gaining momentum (Costa et al., 2022). Broader structural interventions, including regulation, capacity building, and cooperative mitigation strategies, may be essential to enable effective transitions toward net zero that can be adopted more widely in agriculture (Wang and Qiu, 2024).

The CRCF adopts the concept of "additionality", which rewards farmers based on incremental practices and C removals relative to a defined baseline (Cavallin, 2024). However, additionality is debated in the literature and faces rejection from the farmers who began climate-friendly practices before regulatory incentives appeared, since their efforts would not be rewarded (Criscuoli et al., 2024). This highlights the importance of which baseline to select in net-zero certification plans. In the present study, for example, the organic DE farm had already implemented several practices that increased biodiversity and reduced emissions. Consequently, it could not reduce emissions much more and thus had the smallest emission reductions among the four farms. In this case, current certification rules would not recognize the DE farm's long-term environmental commitment.

Furthermore, large knowledge gaps persist in the literature about farm-level GHG accounting, including environmental impacts of mitigation actions, barriers to adoption of mitigation actions by farmers, and effects of mitigation actions on energy use. Further research and development are needed to increase the affordability and adoption of relevant actions (Rosa and Gabrielli, 2023). This study provides valuable insights from four distinct farms, but farming systems differ in management types, soils, and climates, which makes comprehensive farm-level GHG accounting a time-consuming process that requires coordination between data providers and analysts, as well as diverse expertise. Thus, future research should explore a variety of mitigation actions performed on/in a wider range of farm types, geographic regions, and management contexts.

5. Conclusion

In the contexts of the four farms studied, results demonstrate that targeted mitigation actions can reduce GHG emissions greatly at the farm level. However, achieving net-zero GHG emissions remains extremely challenging, and it may not always be possible without decreasing productivity, in particular on livestock farms. We recommend pursuing net-zero GHG emissions as a landscape- or sector-level objective, in which synergies among farms can contribute to larger climate goals.

Actions such as increasing organic fertilization, rewilding farmland, or converting to solar power had the highest GHG-mitigation potential, but their effects on other farm characteristics (e.g., energy use, economic costs, biodiversity, land use) need to be considered. Narrowly focusing on net zero on-farm emissions risks overlooking key dimensions of sustainability or displacing environmental impacts rather than reducing them.

This multi-national case study supports efforts to align farm practices with broader European climate-neutrality targets and provides insights into strengths and limitations of nature-based solutions and technological innovations assessed under real-world conditions. While these actions can contribute meaningfully to mitigation, their effectiveness depends greatly on the farm context. Developing sustainable strategies to reduce GHG emissions that can be adopted more widely in agriculture requires further empirical research, additional data on effects of practices on productivity, more accurate estimates of resource use and SOC stocks, and the support of policies that promote collaboration and long-term transformation across agricultural landscapes.

CRediT authorship contribution statement

Emily Miranda Oliveira: Writing – original draft, Formal analysis, Conceptualization. **Julie Auberger:** Writing – review & editing, Software, Formal analysis, Conceptualization. **Andrea Ferrarini:** Writing – review & editing, Data curation. **Deise Aline Knob:** Writing – review & editing, Data curation. **Amie Pickering:** Writing – review & editing, Data curation. **Michael S. Corson:** Writing – review & editing, Supervision, Formal analysis. **Hayo M.G. van der Werf:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During preparation of this article, EMO used ChatGPT to improve the readability and language of certain subsections of the manuscript. After ChatGPT was used, all authors reviewed and edited the manuscript and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129220.

Data availability

Data are available upon request, excluding any confidential information about farm locations and identities.

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