ClieNFarms
Climate Neutral Farms

D1.5: Catalogue/Reservoir of solutions
Approach for selecting mitigation options and estimating climate impacts

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GHG	Greenhouse gas
LCA	Life Cycle Assessment
SOC	Soil Organic Carbon

1 Executive summary

This report describes the methodology for developing the ClieNFarms Catalogue of Climate Solutions, designed to support European farmers and advisors in choosing and implementing climate solutions. The catalogue contains 33 climate solutions for 6 types of European livestock and arable farms (dairy cattle, beef cattle, sheep, pigs, arable crops, and olive orchards), presented through standardized factsheets with evidence-based information on GHG reduction potential, carbon sequestration, applicability, economic implications, and trade-offs and synergies towards other sustainability aspects.

Targeted users are farmers and advisors, who can use the catalogue to make informed decisions about tailored climate solutions while considering economic viability and integral sustainability. The catalogue can also be used by stakeholders looking for evidence-based information about mitigation options for European agriculture.

Methodology

The following steps were taken in the development of the catalogue:

- Climate solutions were systematically selected using criteria for, e.g., scientific evidence base, technical readiness level, and demonstrated European applicability. From an initial gross list of 690 measures, 33 distinct solutions emerged through literature review and expert validation.
- For the catalogue structure solutions were categorized by agricultural system (dairy cattle, beef cattle, sheep, pigs, arable crops, and olive orchards) and farm sub-system (crop production, fertilization, soil management, energy, feeding, manure management, pasture, animal management).
- More than 100 factsheets were developed across the 6 agricultural systems. The standardized factsheet contains three sections:
    1. Solution information describing the action, mechanism, and applicability conditions;
    2. Climate impacts showing effects on total cradle-to-farm gate GHG emissions (LCA), on specific emission sources, and on soil organic carbon stocks, using six-point Likert scales with average effects and ranges; and an explanation of factors behind variable effects enabling farmers to assess uncertainty and context-specific effectiveness;
    3. Other effects of climate solutions on economic viability (yields, costs, revenues) and environmental and socio-cultural co-benefits or trade-offs.
- Climate impacts were estimated using a 4-step approach:
    - Deriving quantitative estimates based on a literature review of 491 studies (168 meta-analyses, 74 LCA studies);
    - If LCA studies were absent, estimating effects on total GHG emissions based on single source literature results;
    - Converting quantitative results into Likert scale scores for average effects and ranges;
    - Review of factsheets by more than 40 ClieNFarms experts, ensuring that effects derived from literature represent expected impacts in practice across European farms.

Recommendations for further development

Further development should include field testing in diverse systems, user experience assessments to enhance uptake, strengthening the evidence base, and updates incorporating emerging research.

2 Introduction

European agriculture faces unprecedented pressure to reduce its environmental footprint while maintaining productivity and economic viability. The European Climate Law mandates at least 55% greenhouse gas (GHG) reduction by 2030 and climate-neutrality for Europe's economy and society by 2050 (EU, 2021)[1]. In addition, the European Commission committed to the Global Methane Pledge[2], targeting a 30% reduction in methane emissions by 2030. These ambitious targets require substantial changes in agricultural practices across EU farming systems.

The implementation of climate solutions on European farms is central to achieving these climate goals, yet farmers face significant challenges in identifying and implementing tailored and effective climate solutions for their specific farms. There is a large diversity of farming systems in Europe and not all climate solutions are equally applicable and effective in the various farming systems and pedo-climatic conditions. Also, farmers need insight in economic implications and any trade-offs or synergies with food production and other sustainability objectives.

There is already a large body of scientific literature containing evidence on various climate solutions for agriculture, including measures to reduce GHG emissions and to enhance carbon sequestration. However, this knowledge is scattered across hundreds of scientific publications, often presented in technical language, and rarely synthesized in ways that allow direct comparison across solutions or assessment of applicability and effectiveness for specific farm types and pedo-climatic conditions.

The ClieNFarms Catalogue of Climate Solutions was developed to bridge this gap between scientific knowledge and farm-level decision-making. It provides farmers and advisors with a comprehensive, evidence-based resource that translates scientific findings into practical guidance. The catalogue covers 33 climate solutions across European arable crop and livestock systems (dairy cattle, beef cattle, sheep, and pigs), and olive orchards. Each solution is presented through a standardized factsheet that communicates key information in an accessible format. The factsheets indicate the potential for GHG reduction and carbon storage, specify conditions under which solutions are particularly applicable or effective, explain the mechanisms through which effects occur, and provide context on costs and labor requirements, and potential co-effects on other sustainability aspects such as ammonia emissions, soil health, and biodiversity.

This report documents the methodology used to develop the catalogue, including the approach for selecting solutions, the methods for estimating climate impacts and other co-effects, and the expert review process. The catalogue was designed for two primary user groups: European farmers seeking to identify and implement climate solutions appropriate for their specific farm conditions, and advisors supporting farmers in decision-making around climate mitigation strategies. The catalogue may also be useful to other stakeholders, such as policy makers and private sectors seeking evidence-based knowledge about environmental and socio-economic impacts of climate solutions. The methodology was designed to balance science-based evidence with practical usability, to support European farmers in selecting tailored and effective climate solutions.

[1] https://climate.ec.europa.eu/eu-action/european-climate-law_en

[2] https://www.globalmethanepledge.org/

3 Selection of climate solutions

3.1. Scope

Geographical orientation and agricultural systems

The catalogue includes climate solutions applicable to European agricultural systems. In this study this was limited to six types of agricultural systems in demonstration sites of the European ClieNFarms project (https://clienfarms.eu/):

- Dairy cattle (France, Germany, Ireland, New Zealand, Poland, Spain, Switzerland, the Netherlands)
- Beef cattle (France, Ireland)
- Sheep (Romania)
- Pigs (United Kingdom)
- Arable crops (Belgium, France, United Kingdom, Ukraine), and
- Olive orchards (Portugal)

Two agricultural systems in ClieNFarms project, vineyard and tomato production, were not included due to a lack of contributing experts.

System boundaries

Climate solutions in the catalogue concern tangible actions that farmers can take on their own farms, hence within farm gate boundaries. This includes on-farm actions with an impact on GHG emissions or emission removals on the farm and upstream (i.e., production and transport of farm inputs). Purchasing feed ingredients with low embedded emissions, for example, is an on-farm action with an effect on upstream GHG emissions. Actions outside direct farmer control, such as changing agricultural policies or dietary shifts among consumers, are not part of the catalogue.

3.2. Approach for selection

3.2.1. Initial inventory

To establish a first inventory of eligible climate solutions, existing lists of measures were collected from 14 partners in ClieNFarms project in early 2022 (FiBL, BFH-HAFL, CRAW, IDELE, Leeds University, Nutrifarm–Consulai, AgResearch, UNI-ABDN, INRAE, Danone, WR, Teagasc, Arvalis–Terres Inovia–ITB, Terres Inovia, and EGF). Measures were derived from existing sources of scientific and grey literature and databases, and were required to comply with the following criteria:

1) Scope:
    a. Action within farm gate boundaries (see paragraph 3.1);
    b. Applicable and effective in European farming systems, considering the range of climates, soil types, farm structures, and management practices found across Europe;
    c. Maintaining the current main function of the specified agricultural system: food production. Measures that change the main function, e.g. converting agricultural land to nature or using land to produce biobased materials for other sectors, are not considered;

   d. Potentially leading to a reduction in cradle-to-farm gate GHG emissions (based on a life cycle assessment (LCA) approach[1]), and/or increase in carbon stored in agricultural soils. The effect on GHG emissions concerns:
      i. A reduction in absolute emissions, emission per kg of product, or both.
      ii. A reduction in cradle-to-farm gate cumulative methane, carbon dioxide, and nitrous oxide emissions, jointly expressed in CO_2-equivalents;
      iii. Solutions with *solely* an effect on indirect nitrous oxide emissions (e.g., via nitrate leaching or ammonia emission) are not included.
   e. A direct and causal climate impact, not an indirect effect or a precondition/pre-step (for example: rapid removal of slurry from cow barns does not reduce methane emission unless followed by a methane-reducing treatment or storage method).
2) Type of action:
   a. Tangible and concrete action, such as changes in farm management, techniques, purchased materials, or structure of the farm. Not included are, e.g., financial/organizational mechanisms providing an enabling environment for on-farm climate action, or generic terms like 'improve soil management' or 'increase milk yield';
   b. High technical readiness level (TRL 7-9), i.e. demonstrated in practical farms in one or more European countries (not just in an experimental or laboratory setting);
   c. Single measure, rather than a combination of measures or systemic changes (e.g. shifting to other commodity, or changing from conventional to organic production).

This process yielded 54 source documents comprising a total of 690 measures, which were subsequently consolidated and harmonized into a shortlist through the removal of duplicates and refinement of definitions. The shortlist was validated by work package leaders and thematic leaders, and reviewed and endorsed by project partners during a consortium meeting held in October 2022. This iterative process resulted in a list of 139 measures across the six types of agricultural systems.

3.2.2. Final selection

In a next step, a further selection of measures was made during a literature review in 2023/2024 (see Chapter 5) and review of factsheets by experts in 2025 (Chapter 6). In these steps an additional criterion was used for selection of measures:

3) Evidence of effect:
   a. Evidence of effect in at least two peer-reviewed scientific publications;
   b. Consistent evidence of effect, as judged by experts in the review of factsheets.

Based on this criterion, additional measures were excluded due to insufficient or inconsistent scientific evidence. Also, in this step it appeared that some measures did not meet criteria for the initial inventory (criterion 1b and 2b above) and these were also excluded. Excluded measures are listed in Annex 1.

Similar measures were grouped into 'climate solutions' (Table 1). This resulted in a final list of 71 measures, grouped into 33 distinct climate solutions. For each solution, a factsheet was created per farming system. For some solutions relevant across multiple systems, no factsheet was produced for some systems due a lack of system-specific scientific literature, or a lack of time or expertise of project partners. These solutions are indicated with an asterisk in Table 1 (in the online catalogue a link is provided to other systems' factsheets).

[1] Including methane, nitrous oxide and carbon dioxide emissions from on-farm processes, and embedded in purchased materials, fuels, energy, animals, and services (incl. emissions from their extraction, production, processing and transport). Energy exported off-site (e.g. electricity sold to the grid) is not counted as emission reduction (in line with GHG Protocol).

Table 1. Final list of climate solutions and measures in the catalogue.

Sub-system	Climate solution	Measure	Dairy	Beef	Sheep	Pigs	Arable crops	Olive orchard
Cropping plan	Diversify crop rotation	Crop rotation instead of monocropping					X	
		Integrate grass-clover leys into arable rotations					X	
	Cultivate cover crops	Cover crops (all types)	*	*	*		X	X
	Cultivate annual legume crops	Include (more) legume crops in rotations	*	*	*		X	
	Leave crop residues on the field	Retain crop residues on field	*	*	*		X	X
Fertilization	Adapt N fertiliser application	Reduce N dose to prevent overfertilization (right rate)	*	*	*		X	*
		Split N application (vs. one-time)	*	*	*		X	*
		Banded application (vs. broadcasting)	*	*	*		X	*
		Use of synthetic fertilizer vs. no fertilizer use	*	*	*		X	*
	Apply organic fertilizers	Organic fertilizer vs. synthetic fertilizer	*	*	*		X	*
		Organic fertilizer vs. no fertilizer	*	*	*		X	*
	Apply low-emission fertilizers	Controlled-release fertilizers (CRF)	*	*	*		X	*
		Urease inhibitors (UI)	*	*	*		X	*
		Nitrification inhibitors (NI)	*	*	*		X	*
		Double inhibitors (CRF with NI)	*	*	*		X	*
Soil management	Lime soils when required	Lime soils (vs. no liming)	*	*	*		X	
	Reduce soil tillage	Reduced or no tillage vs. conventional tillage	*	*	*		X	*
Energy use and production	Purchase low-carbon energy	Purchase green electricity	X	X		X	*	*
		Purchase HVO	X	X			*	*
	Reduce electricity use	Milk tank pre-cooling	X					
		Heat recovery on milk tank	X					
		Install optimized milk tank	X					
		Slurry heat exchange				X		
		Direct expansion heat pump				X		
		CO2 regulation				X		
		Economic ventilation				X		
		Piglet kennels				X		
	Reduce fuel use	More efficient tractor driving	X	X			*	*
		Improve maintenance and tuning of tractors	X	X			*	*
		Electrify feeding and/or manure scraping (automatic)	X					
	Generate renewable energy	Use home-produced wind energy	X	X		X	*	*
		Use home-produced solar energy	X	X		X	*	*
Manure management	Use anaerobic digestion	Mono-digestion	X	X		X		
	Reduce pH of slurry	Acidification of stored slurry	X	X		X		
	Frequent manure removal	Frequent removal to outside storage				X		
	Capture and treat methane from slurry	Methane oxidation (flaring)	X					
Animal feeding	Feed methanogenic inhibitors	3-Nitrooxypropanol (3-NOP)	X	X				
		Nitrate	X	X	X			
	Increase lipid content of diet	Lipid supplementation	X	X	X			

	Feed plant secondary metabolites that reduce methane synthesis	Essential oils	X	X	X			
		Tannin	X	X	X			
	Use low-emission feed ingredients	Buy concentrate feed with low carbon footprint	X	X	X			
		Buy concentrate feed with low emission factor for methane	X					
		Replace feed ingredients by by-products	X					
		Buy feed ingredients with low carbon footprint				X		
	Optimize the type and amount of concentrates	Optimize dietary concentrate level	X	X	X			
	Optimize starch content of the diet	Increase share of silage maize in diet	X					
	Optimize crude protein content of the diet	Optimize crude protein content of the diet	X	X				
	Improve forage quality	Harvest grass at early maturity stage	X					
Grassland and grazing	Improve grassland management	Optimize N fertilization rate	X					
		Organic fertilizer (vs. no or synthetic fertilizer)	X					
		Liming vs. no liming	X					
		Increase plant species richness	X					
	Incorporate legumes in grassland	Grass-clover vs. grass only	X					
	Improve grazing practices	Optimize stocking rate	X					
		Rotational vs. continous grazing	X					
	Increase or maintain share of permanent pasture	Increase share of grasslands in rotation	X					
		Maintain permanent pasture	X					
	Increase water table in peat soils	Raise water table	X	X	X			
Animal management	Selective breeding	Selective breeding for improved performance (multiple traits)	X	X		X		
		Selective breeding for higher milk yield and solids	X					
		Including methane in the breeding goal	X	X				
		Change from low to high yielding breed	X					
	Improve animal management	Reduce animal health disorders	X					
		Optimize age at first calving	X	X				
		Increase longevity (life span)	X					
		Reduce mortality		X		X		
		Reduce slaughter age		X				
		Reduce (parent) breeding stock[1]		X	X	X		
		Increase animal productivity			X			
		Reduce unproductive animals			X			

[1] For beef cattle: reduce calving interval (breeding cow); for sheep: Increase lamb output per ewe; for pigs: Reduce number of sows per growing pig.

4 Catalogue structure

4.1. Categorization of climate solutions

The final catalogue contains 33 climate solutions distributed across different agricultural systems (Table 1). In the catalogue the solutions are categorized by:

1) Agricultural system: dairy cattle, beef cattle, sheep, pigs, arable crops, and olive orchards, and;
2) Farm sub-system: crop or forage production, fertilization, soil management, energy use and production, feeding and nutrition, manure storage and treatment, pasture management, and animal management.

This allows users to filter solutions by type of agricultural system and sub-system in the presentation format on the website.

4.2. Factsheet contents

Each climate solution in the catalogue is presented through a standardized factsheet. The factsheet structure was designed to communicate information about solutions clearly and concisely to farmers and advisors. It also enables comparison across climate solutions in terms of expected effects. The factsheet is organized into three main sections: information about the solution, climate impacts and other effects.

4.2.1. Section 1: Solution information

This section includes:

- A <u>description</u> of the solution, i.e. the tangible action taken by the farmer;
- A <u>mechanism of effect</u>, explaining how the solution contributes to GHG reduction or carbon storage;
- Information about <u>applicability</u>, describing farming characteristics or situations[1] where the solution is particularly applicable and effective; situations where it is not applicable or not effective; and whether the solution is allowed in organic farming.

4.2.2. Section 2: Climate Impacts

This section presents semi-quantitative information on effects of solutions on GHG emissions and carbon removals. Presented effects show the relative change (%) in GHG emissions and soil organic carbon stocks. The following indicators are used:

1. Total cradle-to-farm gate GHG emissions, particularly useful for food industry climate targets, as these are often based on an LCA approach;
2. Specific emission sources (e.g., enteric methane emission), particularly useful for i) EU countries' national climate targets, as these are often limited to specific gases (e.g., methane or non-CO_2 GHG in agriculture), and ii) farmers and advisors to understand which emission sources contribute to the total GHG emission effect;
3. Soil organic carbon (SOC) stocks, particularly useful to identify options for carbon removals contributing to targets for net zero emissions.

[1] 'Farming situations' refers to biophysical conditions (soil type, climate, topography) and farm structure and management characteristics (herd size, grazing system, feeding regime, manure handling), not socio-economic factors like subsidies or market conditions.

In this section effects are presented *per measure* within a climate solution. For example, the climate solution 'Feed methanogenic inhibitors' covers two specific measures: 3-nitrooxypropanol and nitrate.

Total GHG emissions (LCA approach)

This indicator shows the relative change (%) in total GHG emissions, using a Life Cycle Assessment approach. Gases included are methane (CH_4), nitrous (N_2O) and carbon dioxide (CO_2), jointly expressed in CO_2-equivalents, with GWP characterization factors depending on literature sources used (not harmonized, see Chapter 5).

Cradle-to-farm gate system boundaries are used, covering:

- Direct GHG emissions from the farm operation (Scope 1), including CO_2 emissions from on-farm fuel combustion, CH_4 emissions from livestock enteric fermentation and manure, N_2O emissions from manure management and fertilizer application;
- Indirect GHG emissions from purchased electricity (Scope 2), e.g., for cooling/heating, lighting, or irrigation;
- Upstream emissions (from purchased farm inputs; Scope 3), including emissions from extraction, production and transport of purchased farm inputs (e.g., fertilizers, fuels, pesticides, seeds, animal feed, animals) and manufacturing of farm equipment and machinery. This also includes carbon stock changes associated with land use change, depending on literature sources used (not harmonized, see Chapter 5).

Depending on the agricultural system, different functional units are used:

- For livestock, 2 functional units:
  - 1 kg of main product (for dairy: 1 kg of milk, for beef: 1 kg of live weight, for pigs: 1 kg of live weight, for sheep[1]: 1 kg of live weight or milk)[2] . In other words, the presented effect concerns a change in *relative* emissions per kg of product ('emission intensity').
  - Farm, assuming stable farm size (herd size and land area)[3]. In other words, the presented effect concerns a change in *absolute* emissions per farm.
- For arable crops, 1 functional unit (absolute emission):
  - 1 hectare.
- Different functional units were used in literature sources, which were categorized into emission intensity and absolute emissions (see Chapter 5).

GHG per emission source

This indicator shows the change (%) in absolute emissions per farm (assuming stable farm size) from specific emission sources. For example, a 10% reduction in enteric methane emission per farm. Emission sources differ depending on the agricultural system:

- For livestock (categories in line with FAO GLEAM-3 [4]):
  - CH_4 from animals' enteric fermentation;
  - CH_4 and N_2O from stables, manure storages and treatment;

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[1] Due to very limited literature sources for sheep systems, no distinction could be made between meat- and milk-specialized sheep production, therefore we combined effects on emissions per kg LW and per kg milk. We assumed an equal effect on emission reduction for both products.

[2] The functional unit in the source data may differ from the unit used in the factsheets (see Chapter 5). Also, the method for allocation various depending on literature sources used (not harmonized, see Chapter 5).

[3] In the situation of stable farm size (herd size and land area), the percentage change in GHG emission per farm is equal to the percentage change per ha or per head.

[4] https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/

    - CO_2, N_2O and direct Land Use Change (dLUC) related to feed and forage production (on-farm and off-farm);
    - CO_2 from other direct energy use (e.g. barn ventilation, milking) and embedded in farm inputs other than for feed and forage production (e.g., manure additives or farm equipment and machinery).
- For arable crops:
    - Direct and indirect N_2O emission from soils and crop residues;
    - CO_2 emission from the use of fossil fuels;
    - CO_2 embedded in purchased field inputs (e.g., fertilizer, pesticides, seeds)

Effects per emission source are shown as average effects only (not ranges) and use the same Likert scale as total effects. When there is risk of an adverse effect (where minimum values in the range are unfavorable), this is indicated with an asterisk and explained in the text section on "cause of variable or unfavorable effect."

Soil organic carbon (SOC) stocks

This indicator shows the relative change (%) in soil organic carbon percentage (SOC%). For example, a 10% increase in SOC% compared to the SOC% in the reference situation.

Likert scale

For all indicators the relative change (%) in GHG emission or SOC% is shown on a 6-point Likert scale, showing the direction and the magnitude of the effect. The Likert scale used for GHG emissions and SOC% is shown in Table 2. Thresholds for SOC% were based on EU soil carbon sequestration potential in the EU Soil Strategy for 2030[1]. For GHG emissions thresholds were decided by experts in ClieNFarms project. On the website colored dots are used for the Likert scale to allow rapid insight in effects.

Table 2. Likert scale categories used for relative change (%) in GHG emissions and SOC%.

GHG emission	SOC%
● small decrease (<5%)	● small increase (<10%)
● medium decrease (5-20%)	● medium increase (10-25%)
● large decrease (>20%)	● large increase (>25%)
● no effect	● no effect
● small increase (<5%)	● small decrease (<5%)
● large increase (>5%)	● large decrease (≥5%)

Mean effect and range

Effects are presented both in an average and a range (minimum to maximum).

- The average represents the expected average effect of the measure on a (non-existing) average European farm implementing the measure.
- The range shows the expected variation in effects found in practice across different European farming systems. This variation can arise from several sources, e.g.: regional factors, such as soil type, climate or electricity grid mix; current management practices such as grazing regime, feeding strategy, or manure handling; way or level of implementation, such as dosage rates, application frequency, or technical specifications; and external conditions such as the weather.

The approach for estimating the average effect and the range is described in Chapter 5.

Other information in section 2

- Level of Evidence (LoE): For effects on total GHG emissions and SOC stocks, a level of scientific evidence is presented. The LoE is categorized as follows: High LoE (>2 literature reviews or meta-analyses), Medium (1-2 literature reviews or meta-analyses and/or >5 single studies), or Low (2-

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0699&from=EN

5 single studies, no literature reviews or meta-analyses). Measures were not included in the catalogue in case of less than 2 single studies or a lack of consistent effect among studies (see criteria in chapter 3).
- Cause of variable or unfavorable effect: An explanation is provided of possible reasons behind the variable (incl. unfavorable) effect of measures, as shown in the range (min-max). By knowing the factors that influence the effect, farmers can make informed decisions to increase effectiveness or avoid unfavorable effects.
- Literature references: Literature references documenting the evidence base for climate impacts are included.

4.2.3. Section 3: Other effects

This section presents results of an evaluation of measures regarding their expected effects on technical and economic performance, and potential trade-offs and synergies towards other environmental and socio-cultural sustainability aspects.

The section consists of two parts:

- Expected effects on economic viability (yields, labor time, capital investments, operational costs, and revenues; Table 3), shown using a 7-point Likert Scale ranging from large unfavourable to large favourable effect (with middle score no effect). Thresholds used for a small, medium and large effect are shown in Table 3.
- Expected effects on environmental (other than global warming) and socio-cultural sustainability indicators (Table 4), either shown as potential trade-off (unfavourable effect) or potential synergy (favourable effect).

Indicators were based on Pishgar-Komleh and De Vries (2025). The approach used for estimating effects is described in detail in Chapter 6.

Table 3. Economic viability indicators and thresholds used for evaluation of climate solutions.

Indicator	Description	Thresholds for effect
Yield – animals (not applicable for arable and perennial crop systems)	Yield refers to animal productivity, such as kilogram of milk per cow or live weight gain per animal. In this survey, change in yield (as the main product of farm) is assessed as the percentage of change at animal level compared to the reference situation	Large: >20% change Medium: 5-20% change Small: <5% change
Yield – crops/forage	Yield refers to the amount (in ton dry matter as the main product) and quality of crops (e.g. wheat, barley, tomato) or forage (e.g. grass, maize silage, alfalfa) produced per hectare. In this survey, change in yield is assessed as the percentage of change compared to the reference situation.	Large: >20% change Medium: 5-20% change Small: <5% change
Labor requirement	Labour requirement refers to the amount of human work required to apply a mitigation option, expressed as the additional number of days per year compared to the reference situation.	Large: >20 d/year change Medium: 5-20 d/year change Small: <5 d/year change
Solutions related to animals/feed/manure:		
Capital investments	Capital investments are the upfront costs for essential equipment (e.g., machinery, equipment) and infrastructure (e.g., buildings) needed to establish a GHG mitigation option. They are one-time expenditures, expressed in euros per head of livestock.	Small/medium/large change (€/head): Dairy: <250 / 250-750 / >750 Beef: <200 / 200-550 / >550 Sheep: <40 / 40-120 / >120 Pigs: <20 / 20-40 / >40
Operational costs	Operational costs are the recurring expenses required to keep the production running, including input costs (e.g., fertilizers, seed, energy, feed), labour, maintenance, and waste management. They directly influence the effectiveness of measure. Costs may increase or decrease, and are expressed in euros per head per year.	Small/medium/large change (€/head/y): Dairy: <25 / 25-75 / >75 Beef: <20 / 20-55 / >55 Sheep: <4 / 4-12 / >12 Pigs: <2 / 2-4 / >4

Revenues	Revenue is the total money earned before costs, and it refers to the income (e.g. selling more farm products, or electricity) a business earns beyond current sales. Revenues may increase or decrease (due to lower), and are expressed in euros per head per year.	Small/medium/large change (€/head/y): Dairy: <25 / 25-75 / >75 Beef: <20 / 20-55 / >55 Sheep: <4 / 4-12 / >12 Pigs: <2 / 2-4 / >4
Solutions related to field:		
Capital investments	Capital investments are the upfront costs for essential equipment (e.g., machinery) and infrastructure (e.g., buildings) needed to establish a GHG mitigation option. They are one-time expenditures, expressed in euros per hectare.	Small/medium/large change (€/ha): Dairy: <250 / 250-750 / >750 Beef: <200 / 200-550 / >550 Sheep: <40 / 40-120 / >120 Pigs: <20 / 20-40 / >40
Operational costs	Operational costs are the recurring expenses required to keep the production running, including input costs (e.g., fertilizers, seed, energy), labour, maintenance, and waste management. They directly influence the effectiveness of measure. Costs may increase or decrease, and are expressed in euros per ha per year.	Small/medium/large change (€/ha/y): Dairy: <25 / 25-75 / >75 Beef: <20 / 20-55 / >55 Sheep: <4 / 4-12 / >12 Pigs: <2 / 2-4 / >4
Revenues	Revenues refer to the extra income (e.g. selling more farm products, or electricity) a business earns beyond current sales. Revenues may increase or decrease, and are expressed in euros per ha per year.	Small/medium/large change (€/ha/y): Dairy: <25 / 25-75 / >75 Beef: <20 / 20-55 / >55 Sheep: <4 / 4-12 / >12 Pigs: <2 / 2-4 / >4

Table 4. Environmental and socio-cultural indicators used for evaluation of climate solutions.

Indicator	Description
Ammonia emission	Ammonia emission refer to the release of gaseous NH_3 into the atmosphere, mainly from livestock housing, manure storage, and fertilizer application. The indicator is expressed as total kg NH_3 per farm.
Water use	Water use refers to the amount of freshwater withdrawn, or consumed by a farm or supply chain, particularly ground and surface water (blue water). Examples of favourable effects are reduced water demand or increased water retention. The indicator is expressed as total water use per farm.
Water quality	Water quality refers to the chemical (nitrogen and phosphorus concentrations, pH, dissolved oxygen levels and presence of contaminants such as pesticides, heavy metals, salts), physical (temperature, clarity, sediment load), and biological (presence of pathogens such as E. coli, aquatic biodiversity) characteristics of water that determine its suitability for ecosystems, human consumption, agriculture, and industry. It reflects whether that water is clean, safe, and ecologically balanced.
Land use or occupation	Land use (or land occupation) refers to the amount of land area used on the farm or outside the farm (e.g., for purchased feed), including grazing land and cropland for crop or forage cultivation. The indicator is expressed as total land use per farm.
Soil health	Soil health refers to soil fertility, as well as the biological (microbial diversity and activity, earthworms and other soil fauna, organic matter turnover and nutrient cycling), chemical (balanced nutrient availability, appropriate soil pH, absence of toxic substances such as heavy metals, pollutants), and physical (good soil structure and aggregation, adequate porosity for water and air flow, resistance to erosion and compaction) properties that enable soil to perform multiple ecosystem services.
Biodiversity	Biodiversity refers to the variety of life forms at all levels of biological organization, including species diversity within ecosystems, genetic diversity within species (e.g., different crop or livestock breeds), and ecosystem diversity across landscapes (the range of different habitats, ecological processes, and landscapes).
Animal welfare (only relevant for livestock production)	Animal welfare refers to the physical and psychological well-being of animals, and how well their needs are met in the environments in which they live. It considers factors such as proper nutrition, access to clean water, appropriate housing, health care, ability to express natural behaviours, and protection from pain, suffering, and distress.
Societal and cultural acceptance	Cultural acceptance refers to the degree to which a practice or product is considered suitable and respectful within a community's traditions, values, and lifestyle. It ensures that innovations or measures do not conflict with local beliefs, customs, or eating habits.

Public health	Public health refers to the protection of human health by preventing and controlling risks that arise from agricultural production. This includes, for example, food safety risks (harmful pathogens, chemical residues, or contaminants), zoonotic diseases (diseases spreading from animals to humans), antimicrobial resistance, and environmental health impacts (e.g. air pollution such as particulate matter affecting surrounding communities).
Farm labour safety	Farm labour safety refers to the protection of agricultural workers from injuries, illnesses, and health risks associated with farming activities, through safe working conditions, proper training, use of protective equipment, and implementation of practices that minimize physical, chemical, and biological hazards.

5 Approach for estimating impacts of climate solutions

5.1. Climate impacts

Effects of measures on GHG emission reduction and carbon removal were estimated based on a combination of literature review and expert opinion. The following steps were followed:

1) Literature review to derive quantitative effects;
2) Conversion of quantitative results from literature to a Likert scale score;
3) Review of Likert scale scores by experts.

In case LCA studies were absent, the effect on total cradle-farm gate GHG emissions was estimated using an alternative approach. This approach is described in paragraph 5.1.2 below.

5.1.1. Literature review

A non-systematic literature review was conducted to substantiate the evidence base for selected climate solutions, to ensure effects are based on solid scientific evidence. As indicated in Chapter 3, solutions were included only if effects were reported in at least two peer-reviewed scientific publications, and with consistent evidence of effect (as judged by experts in the review of factsheets). For field emissions and SOC, studies were included only if situated in temperate climate zones comparable to those found in Europe. Meta-analyses and systematic reviews were preferred as evidence sources because they synthesize results across multiple studies and provide more robust estimates of average effects and variability than individual studies. When meta-analyses were not available, evidence from individual peer-reviewed studies was used. Also, the JRC-IMAP database[1] was consulted for identification of eligible studies, and papers with a low quality score in this database were not considered.

For the literature research on soil carbon sequestration, the following criteria were used for inclusion and prioritization of studies:

- If available, a quality score of 75% by the JRC/IMAP database farming practices fiches;
- Individual practices (and baselines) instead of combined practices (studies combining several practices are included in the database);
- Soil sampling with 0-30 cm sampling depth. Studies with a sampling depth of 15 cm or less, and with sampling depth starting at 30 cm, were excluded. Studies with sampling depth of 20 cm were only be included if not sufficient studies were available or in case deeper sampling was not possible because of bedrock/stones. Meta-analysis results were included independent from the sampling depth of individual studies in the database.
- Long term duration of experiments was preferred over short-term experiments. All studies below 5 years were excluded (but included in the literature database).

The following data and studies were excluded: modelled data (like with RothC or other models), sampling below 15 cm soil depth, less than 5 years duration, not representing European crops or crops not part of the ClieNFarms project (e.g., rice), and studies conducted in tropical regions.

The literature was documented in a database comprising 491 peer-reviewed papers, including 194 meta-analyses or review papers, and 89 LCA studies. The number of studies included in the database varies by farming system, with dairy cattle having the most extensive research base for papers on GHG emissions, and arable crops with most papers on SOC sequestration (Figure 1a and 1b, resp.). Of the papers focusing

[1] https://wikis.ec.europa.eu/display/IMAP/Farming+practices+fiches

on single sources (not LCA), most focus on methane (173, of which 48 meta-analyses or literature review), followed by carbon sequestration (134/96) and nitrous oxide (102/64).

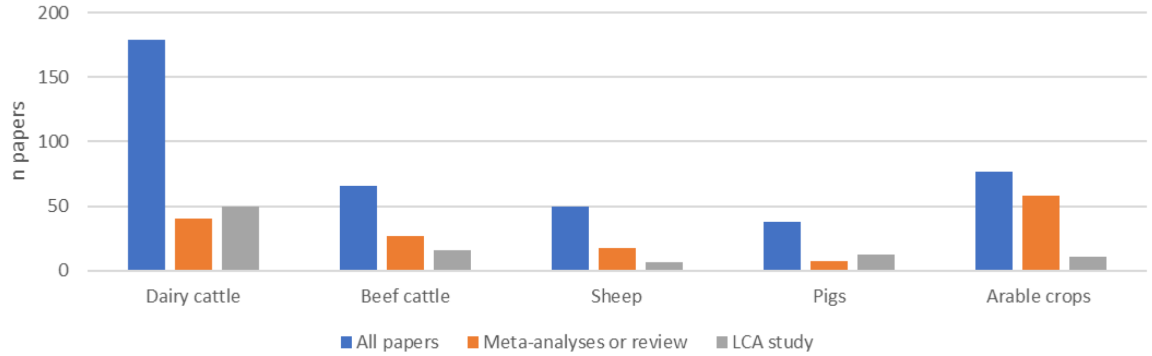

Figure 1a. Number of papers in the literature database focusing on GHG emissions.

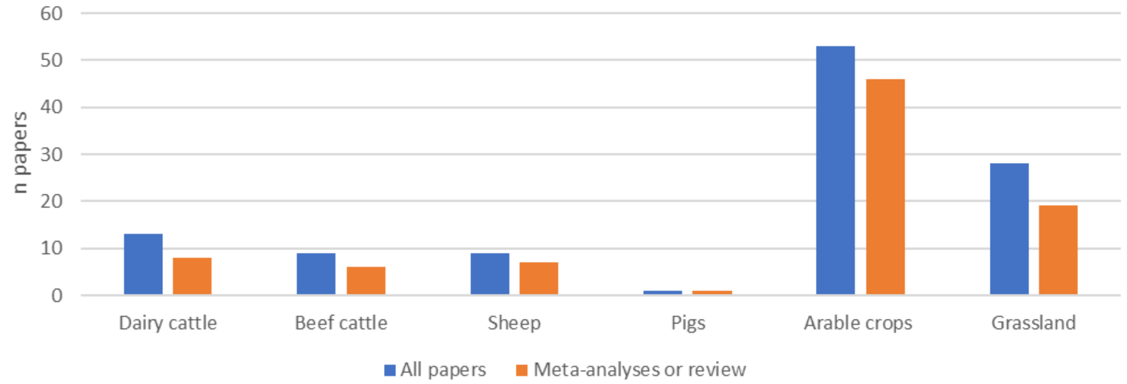

Figure 1b. Number of papers in the literature database focusing on SOC sequestration.

In the database the following information about literature sources is documented:

- Measure name
- Literature reference (author, year, title, DOI link)
- Geographical scale/location (e.g., global, country/region)
- Agricultural system (dairy, beef, sheep, pigs, arable crops, grassland, other)
- System description
- System boundaries/sub-system analysed (e.g. manure CH_4, cradle-to-farm gate LCA)
- Type of study (e.g. experiment, model)
- Gases/sinks (CH_4, N_2O, CO2, LUC, SOC)
- GWP characterization factors
- Intervention
- Comparator/baseline/reference situation
- Change in GHG emission (mean, min, max, 95% CI, s.d., other)
    - Indicator, unit
    - Significant effect (y/n)
- Change in SOC (mean, min, max, 95% CI, s.d., other)
    - Indicator, unit
    - Significant effect (y/n)
    - Sampling depth
    - Duration of experiment (mo)

    - Annual change in SOC% (%)
    - SOC baseline & endline (t/ha)
    - If available: soil type (classification, pH, soil texture), bulk density, crop culture
- n papers in review/meta-analysis
- n observations
- Conclusion

5.1.2. Estimating effects on total GHG emissions

The effects on total cradle-to-farm gate GHG emissions in the catalogue are either based on LCA studies, or on an alternative method to estimate the effect on total GHG.

LCA studies

In case LCA studies were available from the literature review, the effect on total cradle-to-farm gate GHG emissions (in kg CO_2-eq.) was based on those LCA studies. LCA studies, however, often differ in methodological choices, including, e.g., GWP characterization factors used for CH_4 and N_2O, processes included in the cradle-to-farm gate LCA (e.g., including or excluding LUC or SOC-seq.), allocation methods, and functional unit used. As a consequence, quantitative results from studies cannot be directly compared, unless methodological aspects are harmonized. In the catalogue we chose not to correct for differences in methodological choices of studies, but to use direct results from LCA studies and, in order to prevent false precision, convert the results into Likert scale scores. As an extra validation step, the Likert scale scores were reviewed by experts (Chapter 6).

Functional units (FU) used for livestock differ widely. Therefore, FU's used in literature sources were categorized into the FU's reporting i) emission intensity and ii) absolute emissions in the factsheets (see Chapter 4), as follows:

- Livestock emission intensity (g CO_2-eq. / kg product) includes any product-level FU, e.g.
    - for milk: kg or t milk, kg ECM, kg FPCM, etc.;
    - for meat: kg or t live weight (LW), kg carcass weight (CW), kg slaughter weight, kg beef, etc.
- Livestock absolute emission (kg CO_2-eq. / farm) includes all animal- or farm-level FU's, e.g.: per head (or animal), per ha, per farm (provided stable herd size and land area).

Alternative method in absence of LCA studies

In case LCA studies were not available (or partial LCA only), an alternative method was used to estimate effects on total cradle-to-farm gate GHG emissions, with the following steps:

1. Compiling quantitative <u>results of single source gases</u> from literature sources, including all on-farm and upstream processes relevant to the effects of the climate solution;
2. Conversion to total GHG effects by <u>multiplying the emission reduction by the share of each emission source</u> in the total GHG for a specific farming system:
    - For livestock, the breakdown of emissions per livestock system were based on GLEAM 3 data (FAO Global Livestock Environmental Assessment Model) for emissions from livestock in Europe in 2015 (GWP100 set AR6).
    - For arable crops, the breakdown of emissions was based on GHG in UK arable crops (AHDB & CHAP, 2022)[1].

Example of a calculation for dairy cattle:

- For a feed additive reducing enteric methane emission no LCA studies are available;
- Meta-analyses show the feed additive reduce enteric methane emission by on average 28%;

[1] https://chap-solutions.co.uk/wp-content/uploads/2022/08/CHAP_Net_Zero_Report_0822.pdf

- According to FAO data for dairy cattle production in Europe (GLEAM 3), methane from enteric fermentation represents 49% of total carbon footprint (manure CH_4 13%, manure N_2O 9%, feed CO_2 11%, feed N_2O 12%, LUC from soy and palm 1%, and on-farm energy 5%);
- The feed additive has an effect on enteric methane emission only (expert knowledge);
- The estimated reduction in total cradle-to-farm gate GHG emissions is approximately 14% (28% × 49%).

This method was not applied for solutions with complex interactions in the farming system, affecting emissions of multiple processes. In this case, in the absence of LCA studies, the solution was excluded.

5.1.3. Estimating effects per emission source

The effects on GHG emissions per source in the catalogue are derived directly from literature sources, or, if absent in literature, expert knowledge (see Chapter 6). Effects per emission source concern absolute emission (kg CO_2-eq. / farm), and are therefore based on studies reporting animal- or farm-level FU's for livestock, or hectare as FU for arable crops.

5.1.4. Estimating effects on soil organic carbon stocks

Similar to GHG emissions, studies evaluating effects of practices on SOC stocks often differ in methodological choices, such as sampling depths and study duration, and bio geophysical conditions, such as soil type and climate. To avoid large deviations, criteria were applied for inclusion, exclusion, and prioritization of literature sources (see paragraph 5.1.1). After this step, studies were treated the same in further analyses, without corrections or harmonization. For example, selected studies with different sampling depths were treated the same as long as they complied with criteria in paragraph 5.1.1 and included the top soil layer analysis (e.g., carbon sequestration of 0-30 cm sampling was treated the same as 0-100 cm). Soil bulk density changes due to SOC changes were not considered.

5.1.5. Average and range

In the catalogue an average effect and range (min-max) are presented. As explained in Chapter 4, the average represents the expected average effect of the measure on a (non-existing) average European farm implementing the measure, and the range the expected variation in effects found in practice across European farms. These values were derived as follows:

- In a first step, values were derived from the literature review, with a preference for meta-analyses when available:
  - In case of meta-analyses (or literature review), the average effect was based on the average and range was based on the range (typically 95% CI) or coefficient of variation reported in the meta-analyses;
  - In case of single research studies, the average effect was based on the average across the single studies, and the range was based on the lowest and highest value across the individual studies.
- As literature results are often based on experimental conditions or specific farming systems, a verification is needed to ensure the presented average effects and ranges are representing average values and variation encountered in practice in European farming systems. Therefore, in a second step, Likert scale scores based on literature were reviewed by experts in the ClieNFarms consortium (see Chapter 6) to verify that they represent expected effects in European farming systems under practical conditions (not just specific farming systems or experimental conditions).

5.1.6. Conversion to a Likert scale score

In a last step, quantitative literature values were converted to Likert scale scores. Effects are presented on a six-point Likert scale with three levels for favorable effects, one for no effect, and two for unfavorable effects. The Likert scale categories used for relative change (%) in GHG emissions and SOC% are shown in Table 2. All Likert scale scores were reviewed by experts in ClieNFarms project and adjusted based on expert opinion where needed (Chapter 6).

5.1.7. Expert consultation

An important component of the methodology was a comprehensive expert review of all factsheets. The expert input was essential for refining factsheet contents, by validating that effects derived from literature are representative of expected impacts in diverse European farming systems, and providing region-specific and system-specific insights on effects and applicability of solutions. Also, by bringing together different experts, contradictory views were discussed and uncertainties highlighted. Furthermore, experts with more practical experience ensured that explanations (e.g., of mechanisms and variable effects) were clear for the target audience of farmers and advisors.

More than 40 experts from ClieNFarms consortium participated in the review process, each bringing specific expertise in specific agricultural systems, subsystems or research topics. The review process was organized into 7 separate sessions, focusing on specific categories of solutions:

- Animal management
- Feeding and nutrition
- Manure storage and treatment
- Crop production and fertilization
- Grassland and grazing
- Energy use and production
- Soil organic carbon

Sessions were led by designated 'session leads' who coordinated discussion and synthesis of feedback. Names of session leads and reviewers are in Annex 2.

Two sessions were organized for the review process. The first session focused on explaining the factsheet structure and approaches, and the review process. After this first session, experts reviewed factsheets that were allocated to them, including the first 2 sections of each factsheet (see Chapter 4.2). Also, experts scored applicability of solutions to different farming situations via a standardized questionnaire guiding the factsheets. In the second session an in-depth discussion was held about specific issues, including scientific uncertainties, disagreements among experts, solutions with incomplete information, and other concerns affecting factsheet quality or usability. This yielded identification of limitations in the current evidence base, particularly a lack of LCA studies and limited research on certain farming systems (sheep, pigs, extensive systems).

5.2. Yields, cost-effectiveness and co-effects

Besides climate impacts, the factsheets provide information on effects of measures on yields, cost-effectiveness and other sustainability aspects. To this end, a questionnaire was distributed in November 2025 among experts in the ClieNFarms consortium.

In the questionnaire experts were asked to assess expected effects of measures on indicators for integral sustainability listed in Table 3 and 4 (based on Pishgar-Komleh and De Vries; 2025).

- For indicators of economic viability (yield, labour, and cost-effectiveness), effects were assessed using a 7-point Likert Scale, ranging from large unfavourable to large favourable effect (with middle score no effect). Thresholds for a small, medium and large effect are inherently subjective, and were decided upon by expert opinion, per agricultural system (Table 3).
- For indicators of environmental and social/ethical sustainability, answering options were "Unfavourable effect", "Favourable effect", "No effect", or "I don't know" (the latter option was available for economic viability indicators as well).

By structuring the evaluation in this way, the questionnaire allows for the identification of potential synergies and trade-offs across different sustainability domains.

6 Recommendations for further development

The ClieNFarms Catalogue of Climate Solutions provides a synthesis of current scientific knowledge from literature and experts on climate solutions for 6 types of European agricultural systems: dairy cattle, beef cattle, sheep, pigs, arable crops, and olive orchards. It should support European farmers and advisors in farm-level decision-making, providing comprehensive, evidence-based information on 33 climate solutions organized in standardized factsheets, as shown in an example in Annex 3 and presented on the website of the ClieNFarms project: www.clienfarms.eu/solutions.

A number of recommendations are formulated for further development and refinement of the catalogue, and to ensure high uptake by farmers and advisors:

- **Field testing in diverse European systems**: While the catalogue draws on extensive scientific literature, much of this research comes from controlled experimental settings. Field testing of the catalogue in European farming systems is needed to validate reported effects under practical conditions, refine understanding of factors influencing variability, and identify applicability aspects not captured in the present study. The EU project Climate Farm Demo is an example of an excellent opportunity.
- **Enhancing adoption of the tool:** The uptake of decision support tools by farmers and advisors is known to be consistently low due to multiple barriers related to design, delivery, and alignment with real-world decision-making contexts (Rose et al., 2016; Hochman and Carberry, 2011). To enhance adoption of the presented tool, user experience assessments should be conducted with farmers and advisors to identify specific barriers and improvement options.
- **Strengthening the scientific foundation**: Some specific gaps in the scientific evidence base limit the catalogue's comprehensiveness (will be partly covered in EU project Climate Smart Research):
    - Additional LCA studies are particularly needed, as many existing studies focus on single gases or emission sources rather than effects on total GHG emissions;
    - The literature base for some farming systems (sheep, pigs, olive orchards) and specific types of systems (e.g., extensive or mixed systems) is limited and should be expanded;
    - Regarding climate solutions, woody structures should be added to the catalogue, with information on potential effects on carbon sequestration;
    - Regarding climate impacts, effects on albedo could be added (e.g., Sieber et al., 2022);
    - Information about economic viability and other sustainability impacts currently relies on limited expert judgment. Adding a literature base (e.g. via JRC-IMAP) and additional expert judgement for different farm types and regions would strengthen this section.
- **Maintenance and updating**: Scientific knowledge about climate solutions for agriculture continues to evolve, with new solutions emerging and evidence strengthening for existing ones. The catalogue requires regular updating to incorporate new research findings, add newly developed solutions that meet selection criteria, and revise effect estimates as more comprehensive evidence becomes available. Collaboration with the JRC-IMAP database provides potential opportunities.

7 References

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Annex 1. Excluded climate solutions

Excluded solution	Reason for exclusion
Cultivate intersown or inter-relayed crops	Insufficient literature
Grow species or varieties with higher N-use efficiency	insufficient literature
Establish and maintain field margins	takes agricultural areas out of production
Apply biochar to soil	Inconclusive evidence
Improve or maintain drainage of mineral soils	indirect effect
Add chemical additive to slurry	Insufficient literature, inconsistent results
Clean manure storage tank	Insufficient literature, inconsistent results
Shorten manure storage time	Not practical
Use air cleaning system	Insufficient literature
Reduce straw bedding	Insufficient literature
Improve forage quality	Insufficient LCA studies (methane only)
Reduce feed losses	Insufficient literature

Not excluded but combined with another factsheet:

Solution	Combined with factsheet:
Incorporate crop residues in the soil	Leave crop residues on the field
Cultivate permanent herbaceous cover crop in interrows	Cultivate cover crops (for perennial crops - not yet included)
Integrate grass leys into arable rotations	Diversity crop rotation
Establish or maintain hedgerows and individual trees	Establish or maintain agroforestry (not yet published)
Establish or maintain agroforestry	Factsheet not yet published
Use renewable electricity Use biofuels, biogas and biomass Use low carbon heat	Purchase low-carbon energy / Generate renewable energy
Save energy use for milking / in livestock barns / for product storage and processing	Reduce electricity use
Save energy use of vehicles and machinery / for irrigation / Reduce machine fleet	Reduce fuel use
Electrify vehicles and machinery	Purchase low-carbon energy

Generate solar thermal energy and electricity / wind energy / energy from biomass	Generate renewable energy
Cultivate energy crops	Generate renewable energy
Reduce temperature of stored slurry	Frequent manure removal to outside storage
Feed nitrate	Feed methanogenic inhibitors
Improve reproductive management practices / animal health / young stock management / Reduce number of unproductive animals	Improve animal management
Optimize feed ration according to animal requirements	Improve animal management

Annex 2. Reviewers of factsheets

Table A.2. Sessions, names of session leads, and names of reviewers of factsheets in the ClieNFarms catalogue.

Session (lead)	Factsheet	System	Reviewers
Animal management (Pauline Lambert)	Selective breeding	Dairy	Deise Knob, Cesar Resch Zafra, Anouk van Breukelen
		Beef	Josselin Andurand, Mathieu Velghe
		Pigs	Alfons Jansman, Xavier Monger,
	Improve animal management	Dairy	Deise Knob, Cesar Resch Zafra, Pauline Lambert
		Beef	Josselin Andurand, Mathieu Velghe
		Sheep	Gras Mihail, Manole Madalin
		Pigs	Alfons Jansman, Xavier Monger,
Feeding and nutrition (Hassan Pishgar Komleh)	Feed methanogenic inhibitors	Dairy	Cecile de Klein, Amélie Vanlierde
		Beef	Nicolas Lorant, Benoit Rouillé
		Sheep	Catalin Dragomir, Benoit Rouillé
	Increase lipid content of the diet	Dairy	Cecile de Klein
		Beef	Nicolas Lorant, Benoit Rouillé
		Sheep	Catalin Dragomir, Benoit Rouillé
	Feed plant extracts or essential oils	Dairy	Cecile de Klein
		Beef	Benoit Rouillé
		Sheep	Catalin Dragomir, Benoit Rouillé
	Purchase low-emission feed ingredients	Dairy	Theun Vellinga
		Pigs	Alfons Jansman, Xavier Monger,
	Optimize the type and amount of concentrates	Dairy	Jan Grenz, César Resch
		Beef	Benoit Rouillé
		Sheep	Catalin Dragomir, Benoit Rouillé
	Increase starch content of the diet	Dairy	Cecile de Klein, Cesar Resch Zafra
	Reduce crude protein content of the diet	Dairy	Cesar Resch Zafra, Jan Grenz
Manure storage and treatment (Judith Ford)	Install anaerobic digester	Dairy	Karin Groenestein, JIhane EL Mahdi
		Beef	Katja Klumpp, Michael Mathot
		Pigs	JIhane EL Mahdi, Katja Klumpp
	Add acids to slurry (acidification)	Dairy	JIhane EL Mahdi, Katja Klumpp
		Beef	Katja Klumpp, Michael Mathot
		Pigs	Karin Groenestein, Katja Klumpp
	Frequent removal of manure to outside storage	Pigs	Karin Groenestein
	Capture and treat methane from slurry (oxidation)	Dairy	Hendrik-Jan van Dooren
Crop production and fertilization	Cultivate cover crops	Arable crops	Amie Pickering (GWCT), Anne Schneider, Mathieu Dulot, Jan Peter Lesschen (WR)

(Anne Schneider, Marie Collard)	Leave crop residues on the field	Arable crops	Laure Soucemarianadin (ACTA), Mathieu Dulot (TerresInovia), Lin Bautze (FiBL), Jan Peter Lesschen (WR)
	Cultivate annual legume crops	Arable crops	Anne Schneider, Lin Bautze (FiBL) , Jan Peter Lesschen (WR), Wim van Dijk (WR), Didier Stilmant, Marie-Hélène Jeuffroy
	Adapt N fertiliser application	Arable crops	Jan Peter Lesschen (WR), Wim van Dijk (WR), Delphine Hourcade
	Apply organic fertilizers	Arable crops	Amie Pickering (GWCT), Laure Soucemarianadin (ACTA), Emily Miranda-Oliveira (INRAE), Lin Bautze (FiBL) Jan Peter Lesschen (WR), Wim van Dijk (WR), Grégory Véricel, Hans-Martin Krause
	Apply low-emission fertilizers	Arable crops	Amie Pickering (GWCT), Wim van Dijk (WUR), Jan Peter Lesschen (WR), Delphine Hourcade
	Lime soils when required	Arable crops	Laure Soucemarianadin (ACTA), Lin Bautze (FiBL), Jan Peter Lesschen (WR), Catherine Hénault INRAE
Grassland and grazing (Sarah Walsh)	Improve forage quality	Dairy	Jouke Oenema, Cecile de Klein, Alexandre Mertens, Katja Klumpp
	Improve grassland management	Dairy	Jouke Oenema, Cecile de Klein, Alexandre Mertens, Katja Klumpp
	Incorporate legumes in grassland	Dairy	Jouke Oenema, Klumpp
Energy use and production (Anne-Sophie Coince)	Reduce electricity use	Dairy	Jan Grenz, Thomas Gontier
	Reduce fuel use	Dairy	Jan Grenz, Thomas Gontier
		Beef	Thomas Gontier
	Save energy use	Pigs	Judith Ford
	Generate renewable energy	Dairy	Jan Grenz, Thomas Gontier
		Beef	Thomas Gontier
		Pigs	Judith Ford
	Purchase renewable energy	Dairy	Jan Grenz, Thomas Gontier
		Beef	Thomas Gontier
		Pigs	Judith Ford
Soil Organic Carbon (Lin Bautze)	Diversify crop rotation	Arable crops	Laure Soucemarianadin (ACTA), Markus Steffens (FiBL), Jan Peter Lesschen (WR)
	Retain crop residues after harvesting	Arable crops	Laure Soucemarianadin (ACTA)
	Cultivate cover crops	Arable crops	Matthias Kuhnert, Laure Soucemarianadin (ACTA)
	Cultivate legume crops	Arable crops	Matthias Kuhnert, Laure Soucemarianadin (ACTA)
	Apply organic fertilizers	Arable crops	Emily Miranda-Oliveira (INRAE), Matthias Kuhnert, Laure Soucemarianadin (ACTA)
	Adapt fertiliser application	Arable crops	Matthias Kuhnert, Laure Soucemarianadin (ACTA)
	(biochar - removed)	Arable crops	Emily Miranda-Oliveira (INRAE), Amie Pickering (GWCT), Laure Soucemarianadin (ACTA), Markus Steffens (FiBL)
	Reduce soil tillage	Arable crops	Matthias Kuhnert, Laure Soucemarianadin (ACTA), Jan Peter Lesschen (WR)
	Increase water table in peat soils	Dairy	Katja Klumpp, Laure Soucemarianadin (ACTA), , Markus Steffens (FiBL)
	Increase or maintain share of permanent pasture	Dairy	Katja Klumpp, Sarah Walsh, Laure Soucemarianadin (ACTA), Jan Peter Lesschen
	Improve grazing practices	Dairy	Katja Klumpp, Sarah Walsh, Laure Soucemarianadin (ACTA), Jan Peter Lesschen

	Improve grassland management	Dairy	Katja Klumpp, Sarah Walsh, Laure Soucemarianadin (ACTA), Jan Peter Lesschen
	Incorporate legumes in grassland	Dairy	Sarah Walsh

Annex 3. Example of factsheet

Link to online version:
https://clienfarms.eu/dairy-cattle/manure-storage-and-treatment/install-anaerobic-digester/

Solution:	Category:	System:
Install anaerobic digester	**Manure storage and treatment**	**Dairy cattle**

Mainly applicable for:
Large farms, slurry systems (with frequent removal), and farms with a demand for electricity or heat on site

Not applicable or effective for:
Less applicable for farms with (not-pumpable) solid manure and full-grazing systems

Description
Installing an anaerobic digester (AD) in which animal manure is decomposed by microorganisms in the absence of oxygen ('anaerobic'). In this factsheet only mono-digestion (the use of 100% manure or slurry as a feedstock) is included, as there is a risk of higher emissions (fugitive methane, nitrous oxide, ammonia) when other feedstocks are digested with animal manures. The AD process produces biogas and digestate. The biogas, consisting of biomethane and carbon dioxide, can be used in various ways: combusted to produce heat; converted to green electricity using a CHP (Combined heat and Power generator); or separated and the biomethane upgraded to replace natural gas. Digestate can be used as a fertilizer or further processed (e.g. for animal bedding).

Mechanism of effect
Anaerobic digestion (AD) captures methane from manure that would otherwise be released to the atmosphere. It also produces biogas containing biomethane which can be used to generate heat or electricity, or can be purified and used as a replacement for natural gas. In life cycle assessments the benefit of replacing fossil fuel use is only attributed to the farm if the renewable energy is used on the same farm and not sold. In this factsheet we assume that the biogas is combusted in a combined heat and power unit (CHP) to generate electricity and heat. For emission reduction the main benefit of AD is the capture of methane; the benefit of replacing grid electricity will decline as grid supplies are decarbonised.
Nitrous oxide emissions from stored digestate are higher than from undigested slurry in open stores in summer, but this can be avoided by a gas-tight cover. When applied to soils, nitrous oxide emissions from digestate can be higher or lower than from undigested slurry, depending on specific soil conditions. The effect of digestate application on soil organic carbon does not differ from untreated slurry (e.g. Šimon et al., 2015; Barlog et al., 2020). Some CO2 emission is associated with the manufacturing and transport of the AD installation, but this is small compared to the reduction in emissions by AD.

Reference situation
No anaerobic digestion of manure

CLIMATE IMPACTS

Effect on total greenhouse gas (GHG) emissions (LCA)
Mean effect and range in kg CO2-equivalents:

	per kg product mean (min-max)	per farm (absolute) mean (min-max)	Level of evidence
Mono-digestion	🟢🟢 (🔴 - 🟢🟢🟢)	🟢🟢 (🔴 - 🟢🟢🟢)	*High*

Legend:
🟢 *small effect (<5%)*
🟢🟢 *medium effect (5-20%)*
🟢🟢🟢 *large effect (>20%)*
o no effect
🔴 *unfavourable effect*
🔴 - 🟢 *variable effect (depending on farm characteristics or way/level of implemention)*
N/A effect unknown

Effect per emission source
Mean effect on absolute emissions from:

	Animals CH_4	Manure storage CH_4	Manure storage N_2O	Feed and forage production CO_2	Feed and forage production N_2O	Feed and forage production LUC	Barn CO_2
Mono-digestion	o	🟢🟢🟢 *	🔴	o	N/A *	o	🟢🟢

Legend:
🟢 *small effect (<5%)*
🟢🟢 *medium effect (5-20%)*
🟢🟢🟢 *large effect (>20%)*
o no effect
🔴 *unfavourable effect*
** risk of an adverse effect (see 'cause of variable or unfavourable effect')*
N/A effect unknown

Effect on soil organic carbon (SOC) stocks

	Relative change (%) in SOC mean (min-max)	Level of evidence
Mono-digestion	o ( )	*Low*

🟢 *small increase (<10%)*
🟢🟢 *medium increase (10-25%)*
🟢🟢🟢 *large increase (>25%)*
🔴 *small decrease (<5%)*
🔴🔴 *large decrease (≥5%)*
🔴 - 🟢 *variable effect (depending on farm characteristics or way/level of implemention)*
o no effect
N/A effect unknown

Explanation of variable effect
Mono-digestion

Frequent removal of manure to the digester is important for a high reduction of methane emissions. Anaerobic digestion is less effective when slurry is held in pits for a long time. The reduction in greenhouse gas emissions also depends on the composition and characteristics of slurry, and storage temperature. Improper management and functioning of the system can result in leakage of methane from the system, which can offset the GHG mitigation benefits of anaerobic digestion on farms. Incomplete digestion can result in methane emissions from digestate during storage or spreading. There is also a risk of higher nitrous oxide emissions due to increased pH, higher concentrations of available nitrogen, crust formation, and higher temperatures during digestion. Digestate stores should be covered and any further methane emissions captured. If the biogas is used to replace on-farm electricity, heat or natural gas from fossil energy sources, this results in lower carbon dioxide emission, but the size of this effect depends on the quantity and carbon intensity of the energy replaced.

OTHER EFFECTS

Effects on yield and cost-effectiveness

	Yield animals	Yield crops	Labor time	Costs and revenues Investment	Costs	Revenues
Mono-digestion	o	o	🔴 - 🔴🔴	🔴🔴 - 🔴🔴🔴	🔴 - 🔴🔴🔴	🟢 - 🟢🟢🟢

Legend: (thresholds differ per indictor and can be found in the tooltip)

🟢 *small favorable effect*
🟢🟢 *medium favorable effect*
🟢🟢🟢 *large favorable effect*
o no effect
🔴 *unfavourable effect*
🔴 - 🟢 *variable effect (depending on farm characteristics or way/level of implemention)*
N/A effect unknown

Effects on other sustainability aspects	Risks of trade-offs	Potential synergies
Mono-digestion	Farm labour safety, land use, social acceptance	Ammonia emission

Literature references
Mono-digestion

Sajeev et al., 2018	Greenhouse Gas and Ammonia Emissions from Different Stages of Liquid Manure Management Chains: Al
Zhang et al., 2021	The potential of dairy manure and sewage management pathways towards a circular economy: A meta-an
Moller et al., 2022	Agricultural Biogas Production—Climate and Environmental Impacts
Miranda et al., 2015	Meta-Analysis of Greenhouse Gas Emissions from Anaerobic Digestion Processes in Dairy Farms
Scheutz and Fredenslund, 2019	Total methane emission rates and losses from 23 biogas plants
Emmerling et al., 2020	Meta-Analysis of Strategies to Reduce NH3 Emissions from Slurries in European Agriculture and Consequ
Kupper et al., 2020	Ammonia and greenhouse gas emissions from slurry storage - A review
Aguirre-Villegas et al., 2017	Grazing intensity affects the environmental impact of dairy systems
Rivas-García et al., 2015	Environmental implications of anaerobic digestion for manure management in dairy farms in Mexico: a life
Battini et al., 2014	Mitigating the environmental impacts of milk production via anaerobic digestion of manure: Case study of
Vida et al., 2017	The carbon footprint of integrated milk production and renewable energy systems - A case study
Setoguchi et al., 2022	Carbon footprint assessment of a whole dairy farming system with a biogas plant and the use of solid fract
Thomas et al., 2017	Nitrous Oxide Emitted from Soil Receiving Anaerobically Digested Solid Cattle Manure
Shen et al., 2018	Modeling nitrous oxide emissions from digestate and slurry applied to three agricultural soils in the Unitec
Eickenscheidt et al., 2014	Short-term effects of biogas digestate and cattle slurry application on greenhouse gas emissions affectec
Maciel et al., 2022	Life cycle assessment of milk production system in Brazil: Environmental impact reduction linked with ana
Šimon et al., 2015	The effect of digestate, cattle slurry and mineral fertilization on the winter wheat yield and soil quality para
Barlog et al., 2020	Effect of Digestate on Soil Organic Carbon and Plant-Available Nutrient Content Compared to Cattle Slurr