



ClieNFarms
Climate Neutral Farms

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

Due date of deliverable: M24 – Dec. 2023

Actual submission date: M31 – July 2024



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036822

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

Author(s)/Organisation(s)	Matthias Kuhnert (University of Aberdeen)
Contributor(s)	Katja Klumpp, Durba Kashyap, Marion De Vries, Noura Fajraoui, Daniel Goll, Ainhua Ihasusta, Astrid Loriers, Emily Miranda-Oliveira, Haye Van-Der-Werf, Remi Vial, Ke Yu
Work Package	WP2
Due date of deliverable (DoA)	31 December 2023
Actual Submission Date	11 July 2024
Type of deliverable	R (Report)

Document Revision History			
Date	Version	Author/Contributor/Reviewer	Summary of main changes
08/07/2024	1.0	JE Bergez	Check

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the EC)	

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Funding Scheme: Innovation Action (IA) • Topic: LC-GD-6-1-2020

Start date of project: 01 January 2022 • Duration: 48 months

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How to cite this report:

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring, ClieNFarms Consortium (EU-H2020 project GA n°101036822), 2024 [DOI if relevant]

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List of Abbreviations and Acronyms	
GHG	Greenhouse gas
SOC	Soil organic carbon
MRV	Measuring/monitoring, reporting and verification
GHGE	Greenhouse gas emissions

1 Executive summary

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There are a wide range of tools and models available that simulate greenhouse gas emissions (GHGE), soil organic carbon (SOC) changes and co-benefits or other variables that are affected by activities on the ecosystem. Models and tools could be seen as a fast and comparable cheap option to get a GHGE balance for a farm, but this might affect the accuracy of the results. Further, there is an increasing demand for monitoring changes either for political decisions or for carbon certificate trading, which requires fast, accurate and effective options to quantify GHGE. Therefore, the objective of this deliverable is to advise on the use of models and tools for the different purposes and the contributions tools and models can have for different stakeholders. The analysis and conclusions are supported by early and preliminary results of the different modeller groups. Here, the results are not in the focus as an actual analysis of the GHGE balances, but as examples for the data provided and problems or advantages associated with the use of the different tools and models. It should be noted that despite the focus on modelling, the data collection, availability, analysis and quality takes some space in this deliverable, as the quality of tool and model results as well as the choice of the tool and the applicability is linked to available data.

Describing the complexity and quality of tools and models is difficult. Therefore, here the simple Tier approach introduced by the IPCC is used (in short: Tier 1 is simple Tier 3 is complex), which a simplified assumption that the higher the Tier level, the higher is the potential for better results (limitations and short comings of this assumption are outlined in the sections below). There is a correlation in the complexity and the actual application of the tools and models. Farm tools, that target the calculation of the GHGE balance on the farm scale are designed to use data that are available on the farm without additional measurements but use Tier 1 and Tier 2 approaches. Models and tools that are mainly used in researched are developed around the processes, which means that not all input data are available on a commercial farm and running these tools and models requires additional measurements.

The models and tools in ClieNFarms are a good representation of available options. All tools and models are suitable for decision support (with the farm tools easier to use by non-modellers) and they can support direct measurements on the farm. Non model or tool should be used to quantify a complete GHGE balance on a farm without farm specific measurements that represent the heterogeneity of the target variables sufficiently.

The accuracy of models and tools does not meet the accuracy standards that are required for carbon certificate trading of subsidies. In case tools and models should be used for these purposes, they should be only used to support on-site measurements. This is especially the case for carbon fluxes, wither in form of emissions or as SOC changes. Here, only Tier 3 models can provide results of the required quality and also only by sufficient data for running and evaluating the models. Nitrous oxide (N₂O) and methane (CH₄) fluxes show a high uncertainty in measurements and in modelling. Therefore, a use of model calculations for these fluxes (e.g. to estimate off-sets for SOC sequestration) is acceptable as alternative options are also linked with high uncertainty.

In conclusion, models and tools are very useful in supporting other methods to quantify the GHGE balance on a farm, but still show limitations as only option for quantification. As important as the model and tool are the data that are available to run the models and tools. Further improvements of the models and tools require more data sets, especially long term data that are measure following certain standards. The model development is limited to the data availability that will provide the basis for model developments.

2 Introduction

2.1. Purpose of the document

This document will provide an overview and guidelines about the use of different models and tools for quantifying the GHG emission balance for a farm, for a field and to monitor changes for a change in management that targets to reduce the emissions or achieve negative emissions by improved management. This separation is required, as the models and tools are used for different purposes:

- Farm assessment:** Here the objective is the quantification of the farm specific GHG emissions balance as CO₂-equivalent. This includes all process and activities on the farm, but also up-stream (the GHG emission footprint of products imported to the farm). In general, this assessment is made until farm gate.
- Baseline to monitor changes:** Here we describe the i) Baseline for soil carbon (SOC) by Precision Sampling approach developed by AgriCircle, this includes a describing of the method for soil mapping, the potential variability related to other methods and setups and ii) Farm Baseline by Cool Farm Tool (CFT). This describes the set up of the model simulations as a trial to analyse both farm baseline by a reference tool and analyses how realistic a real-life application will be for assessing a farm.
- Use of models/tools in MRV systems:** While the other options consider often the farm scale, in MRV systems a field or a group of fields are considered or a herd or several herds. These groupings can go beyond the farm scale (e.g. fields from different farms). The models could focus on single or a set of management practices that include the applied action rather than simulated the entire farm balance. This would include the directly changed activity, but also affected aspects (e.g. changes in fertilizer management affect nitrogen emissions on the field, fuel consumption, and changes in the contribution of the GHG emission footprint of the fertilizer).

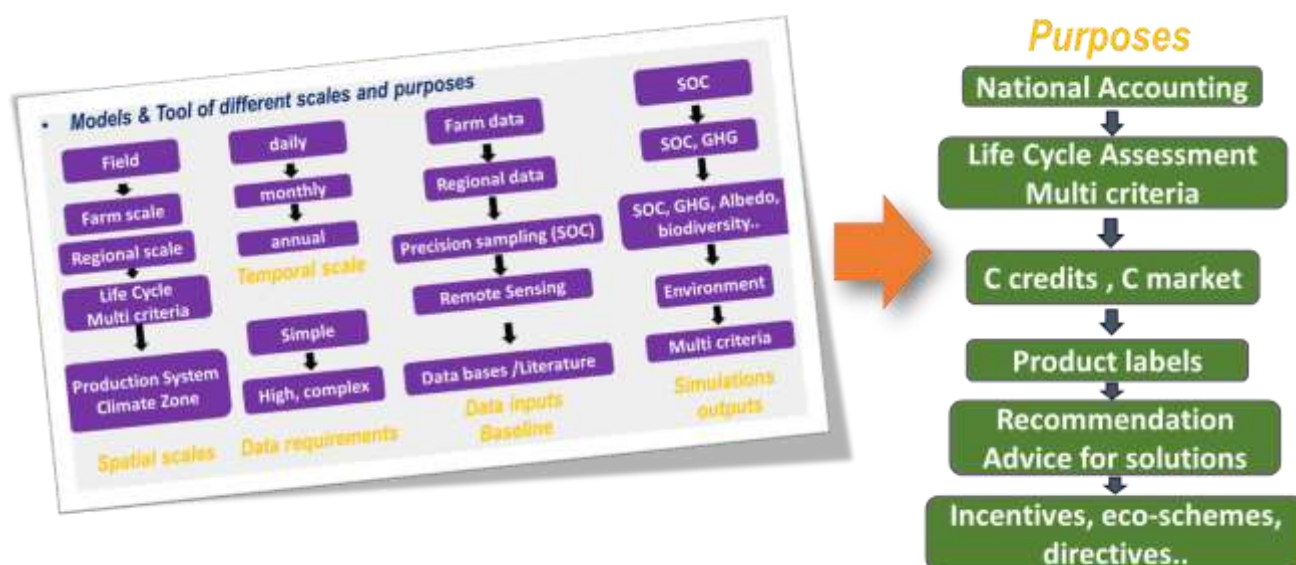


Figure 1: Scheme on different objectives, scales and purpose of models and tool being related with a different data demands.

These different objectives and scales are related with a different data demand.

It should be noted that there is no best model or tool, but each option provides solutions with advantages and disadvantages. The accuracy of the result is here only one factor that is crucial for the comparison, as applicability, data availability, model/tool maintenance, target area (for which part of the world is the model/tool developed/calibrated), target scale, versatility, and others are also crucial factors to consider for the best option for a specific situation.

The guidelines will be more generic for groups of models and tools, based on the use in ClieNFarms. The guidelines include qualitative and quantitative analysis. In conclusion, this deliverable will provide an overview about the usability of the different tools and models for the estimation of soil organic carbon (SOC) changes and different GHGE at different scales. The focus will be on the GHG balance (including SOC) as target variable. The main criteria will be the accuracy, which includes the model complexity (of the structure, data demand and use of the models) and uncertainty and the error of a model approach.

2.2. Structure of the document

The objective of this subsection is to present readers/reviewers the structure of the document, while presenting an insight before the core, which includes the description of the used models, an analysis of the collected and available data as well as an analysis of the applicability of the tools and models and their results. The focus in the ClieNFarms is the farm scale, which is reflected in the analysis of the results and also in the selection of tools and models. Here is an overview about the structure of the document:

Section 3.1 provides an overview about tools and models to simulate agricultural emissions and SOC sequestration. Further, it presents the tools and models that are used in ClieNFarms. The description of the models and tools will help to highlight advantages and limitations of the different options. As simple categorisation the Tier system of the IPCC is used to give indication of processes complexity used, and group the models and tools, accordingly.

Section 3.2 presents the steps from the data collection to the modelling. The models and tools require data and the quality and availability of data affects the quality of the simulation results as well as the applicability. Further, the baseline is defined and explained. ClieNFarms assesses a real-life application of models and tools, which affects the monitoring and affects the definition of the baseline.

Section 3.3 presents simulation results used for Baseline. The modelling exercise requires time as it builds up on other tasks in the project (e.g. data collection). This means that the simulations are not yet completed, but the baseline runs for all farms using the Cool Farm Tool are complete (some gaps due to data availability or functional limitations). Selected results will be presented to support the conclusions.

Section 3.4 presents an analysis of the quality of the simulation results. As data for evaluation are not available, the analysis is mainly descriptive and highlights problems and limitations that were discovered for real-life applications of the models and tools. This includes also the available data sets for simulations and the use of default values. Here it is highlighted how the model results can help to change farm activities toward climate neutral farming.

Section 3.5 presents an analysis of the applicability of the models and tools. This section summarises the findings of the previous sections to provide a discussion for the conclusion. Using the finding of previous sections, the usability of models and tools will be highlighted on the list of models used in ClieNFarms. The contribution to improve farming or to support MRV systems is the main focus in this section.

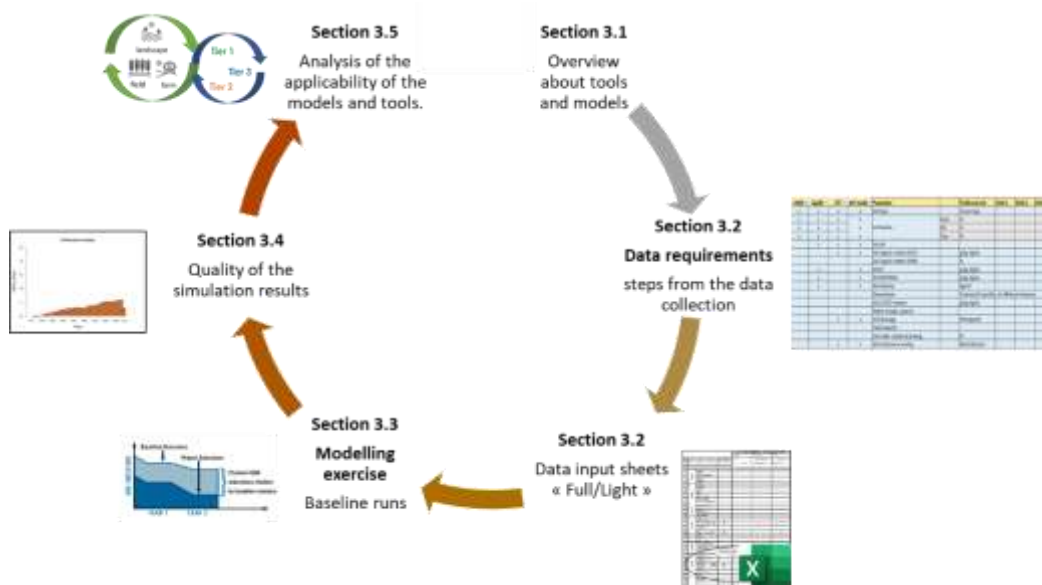


Figure 2: Scheme on the organisation of subsections and information flow in this deliverable.

3 Analysis of available tools and models

3.1. State of the art in GHG emission modelling

Modelling GHG emissions from farming is focussing usually on the three major greenhouse gases carbon dioxide (CO₂), nitrous oxides (N₂O) and methane (CH₄). Respiration of plant, animals and soil organisms, emissions during production of to the farm imported products, energy and fuel consumption are the main sources of CO₂ on the farm. N₂O emissions have crucial contributions to the farm footprint for the cropland emissions and CH₄ for the livestock. N₂O and CH₄ emissions are comparable small to the CO₂ emissions, but their global warming potential make their impacts more relevant in comparison to the CO₂. The global warming potential is a measure of the relative radiative impact of the GHG in the atmosphere. These impacts will be given as relative value in comparison to the impact of CO₂. The used values are usually provided for the impact over a 100-year period with CH₄ showing 27 times and N₂O showing 273 times the impact of CO₂.

Models and tools have different structure and complexity. The IPCC provides a simple categorisation to differentiate the different complexities in a three-step Tier approach. Tier 1 indicating a basic method with an equation and default emission factors, Tier 2 using more developed the same equation but country-/region-specific emission factors and Tier 3 any more complex method, ranging from alternative equations to process-based models (see also Table 1). Tier 1 approaches using generic default factors, which are available for global application or restricted to specific indicators (e.g. climate zone). In contrast, Tier 2 approaches are developed for regional or national applications. The data basis used to develop these factors or equations are location specific, which potentially provides a better accuracy. Available emission factors are summarised in the emission factor database (EFDB; <https://www.ipcc-nggip.iges.or.jp/EFDB/main.php>).

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Table 1: Overview about the categories and complexities of the models.

Tier	Variables Used	Emission Factor	Processes	Type of Models
1	Basic activity data (e.g., total fuel consumption).	Default emission factors provided by IPCC.	General and simplified processes with broad assumptions.	Simplistic and generic models/equations applicable globally without regional customization.
2	Country-specific activity data and more detailed variables (e.g., fuel types, livestock categories).	Country-specific emission factors, more accurate than Tier 1.	More detailed and specific processes relevant to the country or region.	Intermediate models/equations with some customization based on regional specifics.
3	Detailed, high-resolution activity data (e.g., specific industrial processes, local climate conditions).	Facility-specific or technology-specific emission factors	Comprehensive and detailed processes, considering local technologies and practices.	Advanced, often dynamic process-based models tailored to specific circumstances, including simulation and predictive models.

Model complexity and structure depends on the specific objectives the model or tool was developed for. When models or tools are applied on areas where they are not developed for (i.e. on different climate, soil types, animals), this may have an impact on the quality and accuracy of the result. The transferability or applicability of the tool or model must be tested for the target conditions to assure high quality results.

Models and tools simulate one (e.g. carbon models and soil organic carbon models simulate only the carbon emissions) or several GHGs (e.g. DNDC and Cool Farm Tool simulate CH₄, CO₂ and N₂O). The simulation of several GHGs is either organised as parallel (Tier2), independent simulation (e.g. the Cool Farm Tool) or includes interactions between the different cycles (e.g. DNDC, Tier3). Furthermore, on the farm the sections can be divided into cropland/grassland, livestock and other activities. Other activities include heating, transport and other activities that are not directly related to one of the other two activities. Depending on tool and model, fuel consumption or energy (e.g. pumping water for irrigation or fuel consumption for field practices) might be included in the tool, while process-based models often focus on the field or livestock management activities only.

The contributing tools and models also have different target scales (Figure 2). While many tools focus on the farm scale, process-based models (Tier 3) are usually developed for the point or animal scale. In these models fields or the herd are often assumed to be homogenous and the point simulation is associated with the field scale or for the herd. These models are then also used for larger scales by applying the model point by point using different spatial datasets, where each point is often associated with a grid cell or pixel (here a point is often associated with a grid cell, pixel). On the other hand, other spatial or regional models simulate a regional or large- scale average mainly by using empirical functions (Tier1). Farm - specific tools, in contrast, separate the different activities on the farm.

For each activity the emissions will be estimated (mainly by Tier 1 and Tier 2 approaches, though Tier 3 approaches can also be used. Depending on the tool the data may be aggregated for the farm, or an external aggregation of the results might be necessary. These Farm specific tools are often designed for policymakers or farmers but there are farm -specific tools tailored for research. These farm-specific tools

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are designed around the data available on the farm. This farm typically includes very detailed information about management and infrastructure and less environmental details like soil properties, SOC, climate data, biodiversity. Depending on the model/ tool type (tier 1, 2, 3) and purpose the data requirements may differ. To adapt models to the available data there are two major concepts are used. One concept is that tools based on Tier 1 and Tier 2 approaches, use generic factors and equations that do not require environmental data (e.g. ANCA or the Cool Farm Tool (CFT,<https://app.coolfarmtool.org/>; Hillier et al., 2010) The other concept involves linking the tool with a database to provides location-specific environmental data in the background to fill gaps and run process-based models like (e.g. in the Comet Farm Tool (<https://comet-farm.com/>; Paustian et al., 2017).

Additional to farm tools, Life cycle assessment (LCA) tools include all relevant sources for a final product encompassing the entire production chain. These tools include upstream emissions (e.g. imported fertilizer or seeds) as well as emissions for transport and packaging. Some tools the latter is excluded, focusing only simulate until farm gate (the product footprint when leaving the farm). LCA studies can be separated into consequential studies, which quantify environmental changes resulting from demand or production changes, and attributional studies, which quantify the environmental impact on (de Vries et al., 2015).

Similar to the farm tools, LCA tools simulate the emissions based on indicators, generic factors, and simple equation (Tier 1 and Tier 2 approaches). As the LCA models rely on factors and indicator their application depends on the data set used for the development. The conditions of the system that the tool is applied on, should be represented in the data set that was used for the development. This means for national developed tools, the requirement to proof their applicability in other areas. Examples for LCA models that are applied country specific are the ANCA tool (de Vries et al., 2020; Netherlands).

An analysis of LCA tools also highlighted potential misinterpretations in their applications on organic agriculture systems. The product-focused approach focusses on the output of a provided service or good. Additionally, key aspect of sustainable agriculture (e.g., soil health or biodiversity) might be ignored (van der Werf et al., 2020). This is also the case for other tools and models. Analysing and comparing tools and models with each other includes the risk that these aspects are ignored, as some LCA or farm tools provide options to consider additional environmental factors as e.g. biodiversity (e.g. ANCA, Cool Farm Tool).

Process-based models are in the Tier 3 category and show the potential to provide more accurate simulation results due to a better representation of local specifications. Associated with this is usually a higher demand for local environmental data. Beside the information about farm management activities, these models require specific soil data and climate data. In contrast to Tier 1 and Tier 2 approaches, Tier 3 approaches require additional measurements. The **process-based models** can be categorised into **carbon models** (e.g. RothC focussing on the carbon cycle) and **biogeochemical models** that include more than one nutrient cycle (e.g. DAYCENT or DNDC). These models simulate emissions at specific point focusing on individual locations. Areas sharing similar environmental variables can be summarized and spatial data can be employed to enable spatial simulations.

While biogeochemical models focus often on the soil, soil-vegetation-atmosphere-transfer (SVAT) models specifically address the atmospheric component particularly emphasising the gas-exchange between the systems. To in cooperate more details about specific processes (e.g. the gas exchange on the stomata) modelling often requires sub-daily (hourly or half-hourly) time steps. These details also necessitate data to parameterise, calibrate and evaluate the model.

Often, models and tools provide an assessment of the actual GHG emissions. In this project the focus is on an annual balance. The process-based models generate monthly or daily data which are aggregated to derive an annual value. For continuous simulations these models offer sub-annual data that can indicate seasonal changes and the impact of extreme weather periods. Capturing the actual emissions is an assessment for the actual conditions. In contrast, continuous simulations or before -and -after simulations allow the monitoring of changes for specific variables. Generally, LCA and farm tools are developed for assessments, primarily on the farm scale and not for monitoring. Process-based models

being dynamic models and developed for continuous simulations, are best suited for both monitoring and assessments.

The tools and models in ClieNFarms are a fair representation of tools and models available for GHG emission assessments and monitoring. While no SVAT models and only a few biogeochemical models (DAYCENT, RothC, ORCHIDEE) are used, there is a good range of farm and LCA models applied in the project. With ORCHIDEE and SAFY-CO2/SAFYE-CO2 two models are included that use remote sensing data as input data.

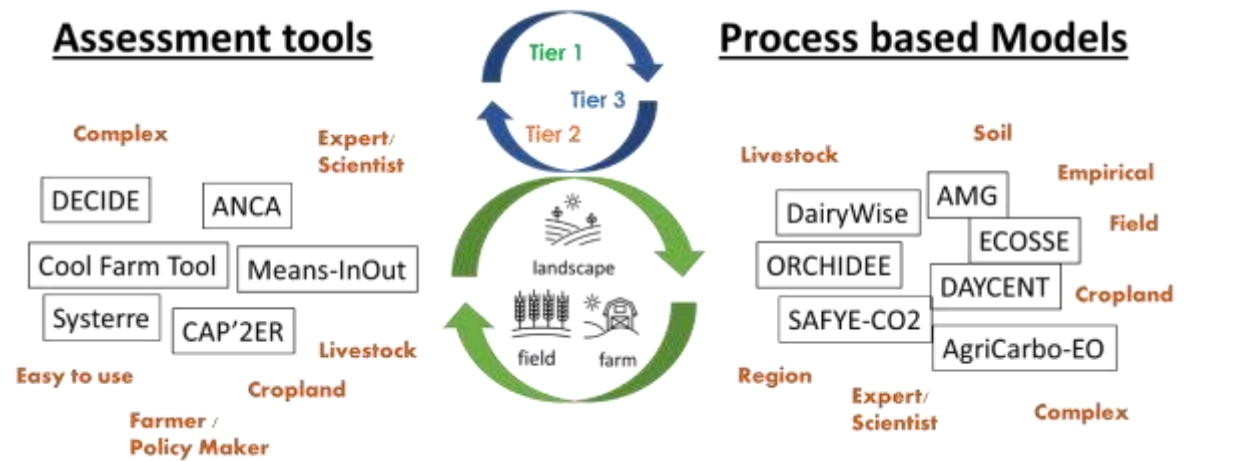


Figure 3: Scheme on used tools and models in ClieNFarms being a fair representation of tools and models, see also table 2 and 3.

3.2. Model and tool descriptions

The models and tools in ClieNFarms can be roughly distinguished by three different categories: farm tools, process-based models and regional models. The most obvious difference is the scale (farm, field, region, respectively), but this is associated with the complexity and detail considered processes are represented in the different models and tools (i.e. Figure 3). Greater complexity or detail does not necessarily mean better results, rather the model complexity should match to a specific objective. Each of the models and tools have their purpose and for specific questions a combination of models and tools often provide the best result. Here, we briefly describe the models and tools used in ClieNFarms are described in a nutshell.

There are different tools and models available, developed for all kind of purposes. There are different possible categories to group these tools and models. The tools used in ClieNFarms are summarized in Table 2. Please find further detail in the Annex.

Table 2: Specifications of the modes and tools used in ClieNFarms. For further details see Annexe.

Name	Scale	Time step	Tier level	Farm type	Included emissions	System	Regenerative energy
Cool Farm Tool	Field, farm	annual	1-2	Dairy, crop, livestock	CH ₄ , N ₂ O, CO ₂	All emissions until farmgate	yes
CAP'2ER	Farm	annual	1-3	Dairy, beef	CH ₄ , N ₂ O, CO ₂ , NH ₃	All emissions	non

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						until farmgate	
ANCA	Farm	annual	1-3	Dairy	CH ₄ , N ₂ O, CO ₂ , NH ₃		
Means InOut	Field, herd	annual	1-2	Annual and perennial crops, livestock	CH ₄ , N ₂ O, CO ₂		
SYSTERRE	Field, farm	Annual	1	Crop	N ₂ O, CO ₂	All emissions until farmgate	No
SAFY-CO ₂ / SAFYE-CO ₂	Field	Daily	3	Crop	CO ₂	Plot system : vegetation and soil	
DAYCENT	field	daily	3	crop	CH ₄ , N ₂ O, CO ₂ , yield, SOC		no
ECOSSE	field	Daily, monthly	3	crop	CH ₄ , N ₂ O, CO ₂ , SOC		no
ORCHIDEE	field	daily	3	crop	CH ₄ , N ₂ O, CO ₂ , yield, SOC	Field (crop and soil)	n/a
DECIDE							
Simeo-AMG	Field	annual	3	Crop	CO ₂ through mineralization on organic matter	Soil	no
LBC-Grandes cultures (and related commercial tools)	Farm	annual	1-3	Arable crops	N ₂ O, CO ₂ (NH ₃)	All emissions until farmgate + some downtream	possibly
MITERRA- Europe	Region	annual	1-2	Crop and livestock	CH ₄ , N ₂ O, CO ₂ , NH ₃ , SOC, NO ₃	On farm emissions	no

Table 3: Functional specifications of the considered tools and models. For further details see Annexe.

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Name	Parameter farm specific ¹	Interface – user friendly	User friendly output	Targeted user	Considering upstream emissions	Requires remote sensing data
Cool Farm Tool	yes	yes	yes	Farmer, advisor, policy maker	yes	no
CAP2'ER	yes		yes	Farmer, advisor, policy maker, researcher		no
ANCA	yes	no	yes	Advisors, researcher	yes	no
Means InOut	yes		yes	Researcher	yes	no
SYSTERRE	yes	yes	yes	Advisors, farmers, researcher	yes	no
SAFY-CO2/ SAFYE-CO2	no	no		Science, farmer, advisor, policy maker	No	yes
DAYCENT	no	no	no	Researcher	no	no
ECOSSE	no	no	no	Researcher	no	no
ORCHIDEE	no	no	no	Researcher	no	yes
DECIDE	yes					no
Simeo-AMG	yes					no
MITERRA-Europe	no	no	no	Researcher	Possibility	no

1 : Farm specific parameters are data that are available on the farm (all farms) without additional measurements. E.g. is the yield and the amount of fertilizer well know, but soil properties are not. Here no indicates that additional measurements are required to get the required data set for the model/tool.

3.2.1. Cool Farm Tool

Short profile: Farm calculator for greenhouse gas (GHG) emission

Tier level: 1-2
Type: Tool for GHG emissions on farm
Key target outputs: CO₂, N₂O, CH₄
Timestep: annual
Scale: field, farm
Farm type: cropland, livestock, dairy

The Cool Farm Tool's (CFT) was developed as a greenhouse gas (GHG) calculator (Hillier et al., 2011; Hillier et al., 2012), but was extended by options for biodiversity and water use. The main intention was to provide product-level calculations of outputting emissions for individual products produced on-farm. The tool can provide the emission footprint for multiple products on the farm, but this has to be assessed separately. The focus is on the emissions of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) as the major sources of on-farm emissions associated with the production of agricultural products. The emissions are provided as CO₂-equivalent, using the latest values for the global warming potential. The emissions are calculated on Tier 1 and Tier 2 approaches as available. The data demand is orientated on data that are available on the farm without additional measurements. Further, the Cool Farm Tool considers a wide range of farm options, covering a wide range of crops and animals. The tool is developed for the farm scale, but is using field specific data to calculate the GHG emissions. The emissions include the footprint of imported goods (e.g. fertilizer) and all actions until farm gate. The Cool Farm Tool is managed by the Cool Farm Alliance, which means that the tool is continuously developing, updated and extended for new options. Beside its use as assessment tool, the Cool Farm Tool was also used to estimate

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impacts of mitigation options to reduce emissions (Hillier et al., 2012). The Cool Farm Tool is a commercial tool, which requires a licence that requires fees for using the tool. The use of the tool is free for farmers and students.

3.2.2. CAP'2ER

Short profile: The objective of the CAP'2ER® tool is to provide advisors and farmers with a multi-criteria environmental assessment tool at the farm, units and product levels.

Tier level: Tier 1 for soil carbon sequestration and 2-3 for other emissions.

Type: Tool to evaluate and reduce environmental impact on farm

Key target outputs: Climate change, energy consumption, nitrogen balance and efficiency, plant protection products use, carbon sequestration, biodiversity, soil management, nutritional performance, autonomy, and economic results.

Timestep: Annual

Scale: Farm and unit and field (cropland CAP'2ER)

Farm type: Livestock (dairy, beef, sheep and goat) and crops farm for level 2 and 2. Poultry and horses only level 1.

The CAP'2ER® was developed as environmental impacts calculator (Moreau et al., 2016). The objective of the CAP'2ER® tool is to provide advisors and farmers with a multi-criteria environmental assessment tool (GHG emissions, Ammonia emissions, soil carbon sequestration, energy, biodiversity, nitrogen balance, etc.) at the farm and product levels. There are two levels of evaluation: Level 1, at the unit level (dairy, beef, goat or sheep) with a simplified methodology to allow a cost and time efficient calculation of the products carbon footprint and raising farmers' awareness on mitigation measures. Level 2 considers the entire farm: crop production, soil, animal and external inputs to the farm. This evaluation allows the calculation of the products carbon footprint and the farm carbon footprint.

Level 2 is used in the context of the French Low Carbon Label and the CARBON AGRI methodology to get carbon credit from GHG emissions reduction.

The tool is managed by the French Livestock Institute and a consortium of advising company, dairy, beef, goat and sheep Board and agri-food company. The tool is used in France and UE and is continuously updated and extended for new production system, pedoclimatic context and mitigation solutions and latest emissions factors (GWP, inputs, etc.). The tool is widely used in farms (30000 farms) and also to elaborate carbon road maps and test new solutions for the French ministry of agriculture and agri-food company.

3.2.3. ANCA

Short profile: Annual Nutrient Cycling Assessment tool (ANCA) model for dairy production systems

Tier level: Enteric methane emissions Tier 3

N₂O emissions from soils Tier 1 (IPCC, 2006) with some of the IPCC emission factors replaced by specific Dutch emission factors for land use and soil type based on Velthof & Mosquera (2011).

Type: LCA tool for dairy farms

Key target outputs: N and P surplus, NH₃ emission, GHG emissions and SOC (RothC)

Timestep: annual

Scale: for GHG: LCA (cradle-to-farm gate) for other impact categories: farm

Farm type: dairy farm

The Annual Nutrient Cycling Assessment tool (ANCA) is developed in the Netherlands for dairy production systems (link to website; ‘KringloopWijzer’ in Dutch). The ANCA tool is used for farm-specific assessment of nutrient cycles in dairy farms and emissions to air, water and soil, including: N and P surplus, NH₃ emission, and GHG emissions. The tool is mandatory for nearly all Dutch dairy farms (industry requirement). Besides its use as management tool, ANCA is increasingly used for rewarding farm environmental performance by the Dutch dairy industry. The input data of Dutch dairy farms, therefore, needs to be of high quality, complete, standardized and verifiable; and is collectively organized and stored in a central database (‘Central Database KringloopWijzer’).

3.2.4. Means InOut

Short profile: Life cycle inventories (LCI) MEANS-InOut for agricultural products

Tier level: 1-2

Type: direct emissions at farm tool, to create Life cycle inventories (LCI)

Key target outputs: N emissions (NH₃, NO_x, N₂O, NO₃), P emissions (as particulate and PO₄), C emissions (CH₄, CO₂), heavy metals and pesticides, land occupation

Timestep: annual

Scale: field level, animal production system

Farm type: any crop or animal production

MEANS-InOut was developed to help the creation of Life cycle inventories (LCI) of agricultural products, ready to be imported in a LCA software (such as SimaPro or openLCA). MEANS-InOut calculates the main pollutant flows due to crop production, at field level, or livestock production at animal production system level. MEANS-InOut also aggregates system inputs and direct emissions to create a life cycle inventory of the studied production.

To do so MEANS-InOut contains a set of models to estimate the emissions of the main pollutants (N, P and C emissions, pesticides, heavy metals), and natural resources use, due to agricultural production. These models follow AGRIBALYSE methodology (Koch and Salou, 2022). It also provides a mapping of inputs of agricultural inputs and reference LCIs of these inputs so as to generate life cycle inventories of agricultural productions. LCA software is required to calculate impact indicators of the products studied, from MEANS-InOut output.

It is possible to create LCIs of a large range of productions: annual crops (including intercrops), grassland, vineyards, tree crops, greenhouse crops, cattle, sheep, goats, pigs, poultry, rabbit and aquaculture. Crop production can be studied in a product-oriented approach or as part of a cropping system, including the crop rotation. The cropping system as a whole can also be studied in MEANS-InOut.

The data demand is orientated on data that are available on the farm without additional measurements. MEANS-InOut is managed by MEANS platform (INRAE and Cirad), which means that the tool is continuously developing, updated and extended for new options. MEANS-InOut is also the main tool for the updating of the agricultural data of the AGRIBALYSE database.

3.2.5. SYSTERRE

Short profile: SYSTERRE® is a multi-criteria assessment tool for cropping systems and farm characteristics

Tier level: 1

Type: Multicriteria assessment model.

Key target outputs: economic indicators (incl. margins), working time, technical indicators (use of pesticides, ...). For carbon : emissions of CO₂ & N₂O (upstream to farmgate)

Timestep: Year (data can be given on a daily base).

Scale: Plot, group of plot, farm

Farm type: Arable crops farms

SYSTERRE® is a multi-criteria assessment tool accessible on a webserver with secure access. It uses a PostgreSQL DBMS to allow networking and interoperability with other databases and tools. Input data is entered in forms allowing a complete description of the system under study (i.e. agricultural equipment, labour, technical itinerary, economic and pedological data). The SYSTERRE® tool enables the cropping systems and characteristics of the farms to be recorded and described with precision. To achieve this, it uses scientifically recognised standardised methods to calculate a panel of 20 indicators (Berrodier & Jouy, 2013). These indicators can be classified in three categories: technical indicators such as working time and number of tool passes, fuel consumption, economic indicators such as economic efficiency of inputs, mechanisation costs, margins, production costs and input use and environmental indicators such as overall nitrogen balance and mineral balance, TFI (treatment frequency index), energy production and consumption, greenhouse gas emissions (Guillaumin et al., 2007). The indicators are calculated from the information recorded and the reference databases. SYSTERRE® is currently being improved throughout H2020 European projects DiverIMPACTS and SmartAgriHubs, notably in order to strengthen the robustness of its calculation, to increase the number of indicators taken into account and to make it accessible to users from more interfaces. The tool also enables to calculate both GHG emissions in a farm.

3.2.6. SAFY-CO2/SAFYE-CO2

Short profile: SAFYE-CO2, parsimonious crop model for crop production, the C and water budget components.

Tier level: 3

Type: Crop model

Key target outputs: Biomass allocation, yield, CO₂ fluxes, water & carbon budget

Timestep: Daily

Scale: Intra-field with AgriCarbon-EO chain or field scale

Farm type: Cropland

The SAFYE-CO2 (Simple Algorithm For Yield, Evapotranspiration and CO2 flux estimates) is a parsimonious (limited number of parametrisation) crop model (Veloso, 2014; Pique et al 2020 a,b) for crop production, the C and water budget components. It uses assimilation of biophysical variables obtained from high spatial and temporal resolution satellite observations such as the Green Leaf Area Index (GLAI) derived from Sentinel-2 satellites reflectance. The assimilation scheme constrains the model to reproduce the observed dynamic of the vegetation (crop, cover crop, spontaneous regrowth, weeds) and its variability at high resolution. Therefore, it can implicitly consider the impact of vegetation stress and farmer's practices (e.g. cover crop seeding and destruction, silage) on the leaf and biomass production.

The model requires few input data to simulate the daily vegetation development and the main ecosystem fluxes (GPP; Gross Primary Production, Ra: plant/autotrophic respiration, and Rh: heterotrophic

respiration). Weather data is limited to 2m air temperature, incoming solar radiation, and precipitations. Soil properties are needed for the Rh and water fluxes. A crop specific parametrization is needed with fixed parameters (e.g. C:N, R10...) in addition to variable phenological parameters and the Light Use Efficiency that are calibrated during the assimilation phase. More importantly, the model does not require detailed information about farming practices. For example, in the case of C budget calculation only data on organic amendments and straw management strategy (exported or not) are needed.

By using a Bayesian assimilation scheme, posteriori distribution of output variables is provided enabling the estimation of mean and uncertainties of variables at pixel level. The model has been associated to such a scheme in the AgriCarbon-EO processing chain (Wijmer et al. 2023).

The model has been validated for several C & water budget components with independent datasets: flux measurements from eddy covariance flux tower (ICOS), destructive biomass measurements in the field and yield data.

To be applicable at regional scale without accurate soil property maps and activity data, the soil respiration in SAFYE-CO2v2.0.5 is estimated based on Delogu et al. (2017) empirical model with soil moisture and temperature as variable inputs. While providing the heterotrophic respiration, this model doesn't provide information about the evolution of the different carbon pools in the soil due to humification and mineralisation, which is needed for a soil carbon budget. For this objective the AMG (see AMG section below) soil model (Clivot et al 2019) is used in this project. The AMG carbon inputs from biomass residues is forced by the SAFYE-CO2 biomass outputs.

3.2.7. DAYCENT

Short profile: DAYCENT a biogeochemical process-based model for cropland and grassland

Tier level:	3
Type:	Biogeochemical model (process-based)
Key target outputs:	CO ₂ , SOC, N ₂ O, CH ₄ , yield
Timestep:	daily
Scale:	field
Farm type:	cropland

DAYCENT is a biogeochemical process-based model, which was developed on the CENTURY model. Simulations running on daily time steps and include all parts of the carbon (net primary productivity and heterotrophic respiration, and simulates the biogeochemical processes of carbon) and nitrogen (nitrate, N-leaching, N emissions) cycles. Additional options are not activated for ClieNFarms (phosphorus, and sulphur cycles). Required weather input data consist of precipitation, and maximum and minimum temperature at daily time steps. DAYCENT simulates SOM decomposition, nitrification and denitrification, plant production and soil water dynamics, which provides all variables relevant for the GHG emission balance and yield. The trace gas sub-model of DAYCENT simulates soil N₂O and NO_x gas emissions from nitrification and denitrification processes. Daily denitrification rates are calculated for each soil layer based on nitrate (NO₃) concentration, heterotrophic respiration (as a proxy for labile C availability), water content, texture, and temperature (Del Grosso et al., 2008). Detailed information about model concepts and mechanisms is described in greater detail elsewhere (Del Grosso et al., 2008). For cropland simulations a wide range of parameters covering the most crucial crops is provided. All field management options can be considered and modified in the model, which makes it an ideal model for analysing impacts of management changes, e.g. for mitigation options.

3.2.8. ECOSSE

Short profile: ECOSSE is a model for soils derived for mineral soils in the RothC

Tier level:	3
Type:	Biogeochemical model (process-based)
Key target outputs:	CO ₂ , SOC, N ₂ O, CH ₄
Timestep:	daily
Scale:	field
Farm type:	cropland

The ECOSSE model was developed to simulate highly organic soils from concepts originally derived for mineral soils in the RothC (Jenkinson and Rayner, 1977; Jenkinson et al. 1987; Coleman and Jenkinson, 1996) and SUNDIAL (Bradbury et al. 1993; Smith et al. 1996) models. Following these established models, ECOSSE uses a pool-type approach, describing soil organic matter (SOM) as pools of inert organic matter, humus, biomass, resistant plant material and decomposable plant material. All processes of both carbon and nitrogen dynamics are considered. Additionally, in ECOSSE, processes of minor relevance for mineral arable soils are implemented (e.g., methane emissions) to have a better representation of processes that are relevant for other soils (e.g., organic soils). ECOSSE can run in different modes and for different times steps. The two main modes are site-specific and limited-data. In the latter version, basis assumptions/estimates for parameters can be provided by the model itself instead of relying on user input. This increases the uncertainty but makes ECOSSE a universal tool that can be applied for large scale simulations even if the data availability is limited. To increase the accuracy in the site-specific version of the model, detailed information about soil properties, plant input, nutrient application and management can be added as available.

During the decomposition process, material is exchanged between the SOM pools according to first order rate equations, characterised by a specific rate constant for each pool, and modified according to rate modifiers dependent on the temperature, moisture, crop cover and pH of the soil. Under aerobic conditions, the decomposition process results in gaseous losses of carbon dioxide (CO₂); under anaerobic conditions losses as methane (CH₄) dominate. The N content of the soil follows the decomposition of the SOM (Fig. 3.4.2), with a stable C:N ratio defined for each pool at a given pH, and N being either mineralised or immobilised to maintain that ratio. Nitrogen released from decomposing SOM as ammonium (NH₄⁺) or added to the soil may be nitrified to nitrate (NO₃⁻). Carbon and nitrogen may be lost from the soil by the processes of leaching (NO₃⁻, dissolved organic C (DOC), and dissolved organic N (DON)), denitrification, volatilisation or crop uptake; C and N may be returned to the soil by plant inputs, inorganic fertilizers, atmospheric deposition or organic amendments. The soil is divided into 5cm layers, so as to facilitate the accurate simulation of these processes down the soil profile.

3.2.9. ORCHIDEE-CROP

Short profile: ORCHIDEE-CROP regional carbon–water–energy land surface model model for Croplands

Tier level:	3
Type:	Biogeochemical model (process-based)
Key target outputs:	GPP, SOC, yields, albedo, energy balance, evapotranspiration
Timestep:	30 minutes
Scale:	field
Farm type:	cropland

ORCHIDEE-CROP (Xu et al. 2016; doi:10.5194/gmd-9-857-2016) consists of a generic crop phenology and allocation module from the STICS agronomical model integrated into the carbon–water–energy land

surface model ORCHIDEE model. The aim is to simulate the spatial distribution and variability of crop production and its water, energy, and carbon fluxes (including long-term soil carbon changes). ORCHIDEE-CROP resolves major processes governing the coupled carbon–water–energy cycles at the land surface (Krinner et al 2005; doi:10.1029/2003GB002199), computing albedo, roughness, and sensible and latent heat fluxes on 30 min steps (which are required to allow coupling with a global circulation model). The model can be run either coupled with a global circulation model or forced by meteorological information, atmospheric carbon dioxide concentration, soil types and land cover (change). In the latter case the spatial domain can vary from single field to global. It resolves two generic crop types: a C3 crop calibrated on winter wheat and C4 crop calibrated on maize. The model includes soil moisture controls on photosynthesis and plant growth, as well as simplified nitrogen limitation and fertilisation effects without resolving the nitrogen cycle (Xu et al. 2016; doi:10.5194/gmd-9-857-2016)). Resolved crop management activities include seeding, harvest, fertiliser application and irrigation. The baseline version of ORCHIDEE-CROP simulates surface albedo as a function of prescribed time-invariant crop albedo (0.1 in visible & 0.4 in near infrared band in case of winter wheat), dynamics of leaf area index, and a background albedo which is based on coarse-scale (0.5°, monthly) MODIS surface albedo, representing an average seasonal variation of background albedo at the location. Recently, crop yield and harvest dates were calibrated based on 1040 winter wheat rotation in Germany (Yang Su et al. in review).

3.2.10. DECIDE

Short profile:	Life Cycle Assessment (LCA) tool for Belgium to evaluation greenhouse gas (GHG) emissions and energy consumption of farms.
Tier level:	2-3
Type:	LCA based tool at farm scale
Key target outputs:	GHG emissions (CO ₂ eq., CH ₄ , CO ₂ , N ₂ O), energy consumption, NH ₃
Timestep:	one year
Scale:	Farm, workshop, product (milk or meat)
Farm type:	cattle (dairy and beef), sheep, cropland and mixed farms

Based on the Life Cycle Assessment (LCA) methodology, DECiDE is a tool developed by the Walloon Agricultural Research Centre in Belgium. It enables the evaluation of the environmental impacts of farms. Currently, it calculates the greenhouse gas (GHG) emissions, ammonia emissions, and energy consumption of farms.

GHG emissions are expressed in kg CO₂ equivalent (GWP 100, IPCC 2023), energy consumption in MJ, and ammonia emissions in kg NH₃. As recommended by the LCA methodology, DECiDE takes into account both direct emissions (produced on the farm itself) and indirect emissions (arising, for example, from the transportation or production of inputs). The tool thus includes in its assessment all flows from the extraction of raw materials to the farm gate.

The data collection necessary for carrying out the assessments is based on farm-available data without additional measurements. Generic databases are also used (soil, climatic, zootechnical, phytotechnical data, etc.). For these data, specific data on Walloon agricultural practices have been collected.

To improve understanding and facilitate the analysis of results, these assessments are complemented by other environmental indicators (nitrogen balance, agroecological measures), economic indicators (gross margin, EBITDA, agricultural labour income, etc.), and technical indicators (feed autonomy).

It is possible to compare the results of one's farm with the median results of similar farms or to choose to be compared to another farm typology. To limit encoding time, a module for importing agricultural

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accounting data directly into the tool is available. Users can also run simulations and export their data in csv format.

The DECiDE tool is operational for arable farms, dairy and/or beef cattle, and sheep farms in Wallonia. Assessments are available at the farm level (per hectare of UAA) and for products (per liter of standardized milk, per kg of live weight sold, per hectare of commercialized crops).

The tool is available for free at www.decide.cra.wallonie.be. It provides encoding assistance and is supported by a helpdesk. The assessment results can be viewed online and downloaded in pdf format.

3.2.11. AMG

Short profile: AMG soil model

Tier level:	Tier 3
Type:	Soil model
Key target outputs:	Soil organic carbon stock variation
Timestep:	Annual timestep
Scale:	Field
Farm type:	Cropland

The AMG soil model (Clivot et al 2019, Andriulo et al 1999) predicts the soil organic carbon stock changes in the topsoil of arable lands at an annual time scale. It contains 3 pools of carbon: the first one is the carbon input to the soil, corresponding to crop residues, cover crops or organic amendments. One part of this carbon input is humified and the other one is transferred to the active carbon pool of the soil, hence the second pool of the model. This pool will be affected by mineralization process whereas the last pool, the stable carbon pool will be constant during the prediction time (<100years) as it supposed to be completely recalcitrant to mineralization.

The mineralization process depends on 1) the climatic conditions (mean annual temperature, precipitation, evapotranspiration) and irrigation data that are used to calculate a proxy of soil moisture and 2) the soil properties such as clay, CaCO₃, but also pH and C/N ratio that have been added in the last version of the model (Clivot et al 2019). The model has been validated with independent diachronic dataset (Le Noë et al 2023). The AMG Model prediction accuracy has been evaluated on data issued from 20 mid and long-term French trials, in which SOC had been measured at several dates. The field experiments were carried out between 1970 and 2015, and exhibited contrasted soil physicochemical parameters (clay, silt, CaCO₃ and sand content) and climatic conditions (Clivot et al., 2019). The prediction error of the model is evaluated to 5.3 % while that of stock C measurements is 4.6%. AMG model has also been validated in European and Chinese trials and on Andosols from Reunion Island.

SIMEOS-AMG is available on the web pages and is only one of the tools which are using AMG, all of them being coordinated by AMG Consortium in order to ensure coherent results when the AMG-based tools are further developed in specific contexts.

For the "Label bas carbone" reference certification methodologies in France, the French ministry has asked the INRAE experts (through its agency ADEME) to carry a comparison among all the models dealing with carbon storage in the agricultural soils and the conclusions underline that AMG is recognised as the most relevant model for that purpose.

3.2.12. DAISY

Short profile: DAISY mechanistic model comprehensive Soil-Plant-Atmosphere System Model

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Tier level:	Tier 3
Type:	Soil-Plant-Atmosphere System Model
Key target outputs:	Soil organic carbon stock variation
Timestep:	Daily
Scale:	Field
Farm type:	Cropland

The mechanistic model DAISY, developed at the University of Copenhagen, is a comprehensive Soil-Plant-Atmosphere System Model. It is designed to simulate the intricate physical and biological processes within an agricultural ecosystem. This approach predicts crop growth and yield based on water availability, nutrient limitations, and weather conditions and simulates the crucial spatial and temporal dynamics of soil organic carbon (SOC). DAISY helps researchers understand the complex interplay between factors like crop residue incorporation, tillage practices, and nitrogen fertilization that significantly impact SOC. The model includes a sophisticated decomposition module that differentiates between various organic matter pools with different decomposition rates. This provides a nuanced understanding of how factors like residue quality (e.g., C:N ratio) and soil conditions (e.g., temperature, moisture) influence SOC decomposition. As SOC decomposes, it fuels microbial activity, which in turn influences decomposition rates and nutrient cycling. Simulating these feedback mechanisms gives a more holistic picture of the soil ecosystem.

Moreover, scenario analysis within the model enables the prediction of potential outcomes of future management practices or changes in SOC. By simulating various scenarios, researchers can identify practices optimizing crop production while promoting SOC accumulation, leading to healthier soils and a more sustainable agricultural future. Additionally, DAISY can explore the potential impacts of climate change on SOC dynamics by simulating changes in temperature, precipitation patterns, and atmospheric CO₂ levels. This facilitates developing adaptation strategies to maintain or enhance SOC under a changing climate.

While powerful, it is important to recognize that the complexity of DAISY requires detailed data inputs and may need calibration with field data for the most accurate results. Extensive data requirements include detailed information on soil properties, weather patterns, crop characteristics, and management practices. Interpreting model outputs necessitates a solid understanding of the underlying biogeochemical processes. For accurate simulations, DAISY often requires calibration with field data from the specific location being studied to ensure the model accurately reflects the unique characteristics of that soil-plant system. Model validation with independent data sets is crucial to ensure the model's generalizability. The standard one-dimensional nature of DAISY might not fully capture the spatial variability of SOC within a field. However, some DAISY versions include two-dimensional transport models to account for spatial variations in factors like soil properties and topography.

DAISY encapsulates several crucial physical processes:

- **Soil Water Dynamics:** Modelled using Richards' equation in one or two dimensions, reflecting water movement within the soil matrix under varying moisture conditions.
- **Heat and Solute Transport:** This is described by the convection-dispersion equation, which accounts for thermal and solute fluxes within the soil. The domain can be partitioned into mobile and immobile zones, with bio pores serving as a third domain, facilitating rapid water and solute movement.
- **Soil-Vegetation-Atmosphere Transfer (SVAT):** Models the exchange of water and energy between the soil, vegetation, and atmosphere, considering factors such as leaf canopy shading and microclimatic conditions.
- **Nitrogen and Organic Carbon Dynamics:** Incorporates processes of nitrogen cycling and soil organic matter turnover, influenced by factors like temperature, moisture, and soil clay content.
- **Crop Growth:** Enables the simulation of diverse management strategies and crop rotations, capturing the interplay between agricultural practices and SOC dynamics.

In our project, we will use DAISY to simulate SOC dynamics. This requires inputs on weather conditions and soil texture to calculate SOC change. Accurate characterization of the soil profile is essential, often obtained from measurements and farm data.

For further insights into the model's functionality, detailed documentation is provided in the reference manual (Abrahamsen, 2000). In conclusion, DAISY offers a powerful platform for simulating SOC dynamics, promoting a deeper understanding of the complex processes involved. By considering the capabilities of the DAISY, researchers can develop innovative management strategies that optimize crop production, enhance soil health, and promote sustainable agricultural practices with a focus on soil carbon sequestration. However, careful consideration must be given to the model's complexity, data requirements, and the importance of calibration and validation for accurate simulations.

3.2.13. RothC

Short profile:

Tier level:	Tier 3
Type:	Soil model
Key target outputs:	Soil organic carbon stock variation
Timestep:	monthly timestep
Scale:	Field
Farm type:	Cropland, grassland

The Rothamsted Carbon Model (RothC), developed at Rothamsted Research, UK, is designed to simulate the turnover of organic carbon in non-waterlogged topsoil (Coleman and Jenkinson, 1996). RothC is a powerful mechanistic tool for simulating the complex dynamics of soil organic carbon (SOC) within terrestrial ecosystems. Its core strength lies in representing SOC as distinct organic matter pools, each with its decomposition rate. RothC emphasizes the decomposition and stabilization of organic matter within the soil, dividing it into several distinct pools:

- Decomposable Plant Material (DPM) Pool: This pool represents fresh plant material with a rapid decomposition rate, characterized by high turnover reflecting easily decomposable organic inputs.
- Resistant Plant Material (RPM) Pool: This pool consists of plant material decomposing more slowly, representing lignified tissues and other recalcitrant organic matter.
- Microbial Biomass (BIO) Pool: This includes living microbial biomass that actively decomposes organic matter, which is crucial for the microbial-mediated transformation of organic carbon.
- Humified Organic Matter (HUM) Pool: This pool represents stabilized organic matter decomposing very slowly, contributing to long-term SOC storage.
- Inert Organic Matter (IOM) Pool: Contains organic carbon, such as charcoal, resistant to decomposition and considered inert on a decadal timescale.

In this modeling exercise, RothC stands out for its minimal reliance on site-specific data and basic input requirements. This characteristic makes RothC well-suited for simulations in contexts where comprehensive information may be scarce or where operations need to cover large spatial arrays. Moreover, RothC's simplicity and reduced complexity make it attractive for scenarios requiring streamlined processes or limited computational resources. Its effectiveness with less data intricacy enhances its applicability across various simulation tasks, ensuring robustness and efficiency in modeling environmental and agricultural systems. The RothC Model requires detailed input data, including:

- Climate Data: Monthly average temperature and precipitation, along with potential evapotranspiration.

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- Soil Data: Soil texture (sand, silt, clay content), bulk density, initial SOC content, and moisture retention characteristics.
- Vegetation Data: Information on the type and quantity of plant residues returned to the soil, including their decomposition characteristics.
- Management Data: Detailed descriptions of land management practices, such as cropping patterns, tillage intensity, and the application of organic amendments.

RothC employs a first-order kinetic approach to simulate the decomposition of each pool. This means the rate of decomposition is directly proportional to the amount of material remaining. As the model progresses, it tracks the transfer of carbon between these pools based on their decomposition rates. For example, the decomposition of DPM releases carbon that microbes can respire, lose as leachate, or contribute to the formation of more stable RPM and HUM pools.

Critically, RothC incorporates the influence of several key environmental factors on SOC decomposition. Climate plays a significant role, with higher temperatures generally accelerating decomposition and increased moisture stimulating microbial activity. Clay content also has a considerable impact, as clay minerals can physically protect SOC from decomposition by adsorbing organic matter onto their surfaces. Finally, the quantity and quality of plant litter entering the soil significantly influence SOC dynamics. Higher inputs of organic matter, particularly those with a high nitrogen content, can stimulate microbial activity and promote SOC accumulation.

RothC adjusts decomposition rates based on empirical relationships between soil temperature, moisture, and organic matter quality. It also simulates the effects of various land uses and management practices on SOC dynamics. Accurate parameterization of decay constants for SOC pools and factors affecting decomposition rates is essential for reliable model outputs. By offering a balance between accuracy and computational efficiency, RothC provides a practical solution for researchers and practitioners working in fields where detailed site-specific information may be challenging to obtain or where large-scale simulations are required. Its adaptability to diverse conditions and its capacity to produce reliable results make it a valuable tool in addressing complex environmental and agricultural challenges.

While RothC offers valuable insights for researchers and agricultural practitioners, it's important to acknowledge some limitations. The model requires specific data inputs for accurate simulations, including detailed information on soil properties, climate data, and characteristics of plant litter inputs. Additionally, the standard RothC model is one-dimensional and may not fully capture the spatial variability of SOC within a field. Furthermore, the model does not explicitly simulate the complex interactions between soil microbial communities and SOC dynamics. Despite these limitations, RothC remains a valuable tool for understanding and predicting SOC changes in terrestrial ecosystems. Its ability to account for various influencing factors makes it a powerful resource for researchers and land managers alike. As research and model development continues, RothC's capabilities are likely to evolve, further enhancing our understanding of soil carbon cycling and its role in global climate change mitigation strategies.

3.2.14. MIDTERRA-Europe

Short profile:

Tier level:	1-2
Type:	Regional emission model (empirical, emission factor-based)
Key target outputs:	CO ₂ , SOC, N ₂ O, CH ₄ , NH ₃ , NO _x and N leaching and runoff
Timestep:	annual
Scale:	NUTS2 region
Farm type:	Cropland, grassland and livestock

MITERRA-Europe is a deterministic emission and nutrient flow model, which calculates greenhouse gas (CO₂, CH₄ and N₂O) emissions, nitrogen emissions (N₂O, NH₃, NO_x and NO₃), N and P flows and soil organic carbon stock changes on annual basis, using emission factors and leaching fractions. The model was developed to assess the effects and interactions of policies and measures in agriculture on N losses on a NUTS-2 level in the EU-28 (Velthof et al., 2009; de Vries et al., 2011).

Input data consist of activity data (e.g., livestock numbers and crop areas and yield from CAPRI, Eurostat and FAOSTAT), spatial environmental data (e.g., soil and climate data), GHG emission factors (IPCC and NIR), and NH₃ emission factors, excretion factors and manure management system data (GAINS). For soil carbon, the calculation rules of the well-known soil carbon model RothC are used. The model includes measures to simulate carbon sequestration and mitigation of GHG and NH₃ emissions and NO₃ leaching. The model can also assess all GHG and nitrogen emissions following a LCA approach until the farm-gate (Lesschen et al., 2011). Effects of mitigation policies and measures can be assessed, as are long-term scenarios (e.g., de Wit et al., 2014), based on activity inputs from agricultural economic models (e.g., CAPRI or AGMEMOD). MITERRA-Europe is not used in the model comparison as described in this report, but will be used in Task 4.4 on the EU-wide scenarios for pathways towards climate neutral farms.

3.2.15. Label bas carbone Grandes culture (LBC-Grandes cultures)

Short profile:

Tier level: Tier 1 for GHG emissions (based on GESTIM+ references) and Tiers 3 for soil carbon sequestration (including AMG model).

Type: A tool to evaluate and reduce environmental impact from arable cropping based farm

Key target outputs: Climate change, carbon sequestration, energy consumption, nitrogen release, plant protection products use, biodiversity, autonomy, and socio-economic results.

Timestep: Annual

Scale: arable crop areas of a farm

Farm type: Arable based farms

The “LBC-Grandes cultures” has been developed as a reference French method by experts based community (Soenen et al., 2021) and approved by the French Ministry dealing with agricultural transition. It is used in the context of the French Low Carbon Label.

The objective of the “LBC-Grandes cultures” is to provide advisors and farmers with a GHG and carbon storage tools including co-benefits assessments multi-criteria environmental assessment tool (GHG emissions, soil carbon sequestration, ammonia emissions, energy, biodiversity, etc.) at the arable farm level. This evaluation allows the calculation of the farm carbon footprint and to get carbon credit from GHG emissions reduction.

The method is managed by the French arable crop consortium and related professional representatives of arable crops in France. It has been developed in a series of commercial application tools such as CarbonExtract, MyEasyCarbon, Sysfarm, Cap2ER-Grandes cultures. The method and tools are used in France and is continuously updated (versioning 2 to come in 2024). The tool is widely used in farms with several projects to elaborate carbon road maps and test new solutions for the French ministry of agriculture and agri-food company.

3.3. Simulations of the farms

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

Farm-specific simulations require farm-specific data sets. The data collection process was guided by the data demands of the different tools and models, with the flexibility to provide data as available. Except for SOC measurements, no additional measurements were conducted.

3.3.1. Data collection

The wide range of models necessitated extensive data due to varying requirements. Several tools share similar demands for farm management data, designed around typical farm data availability. Tools like Cool Farm Tool, ANCA and CAP2’ER were used as basis to provide a reduced list of data to complete, which would allow to run these three tools. However, this only marginally reduced the workload for I3S managers, it was well-received and enhanced data transfer efficiency.

Overall, the full list of requested data containing 6-93 main variables (in total 232 data entries are possible) and the light list (63 main variables) strikes a balance between the model demand and minimizing the workload for I3S managers (Figure 4).

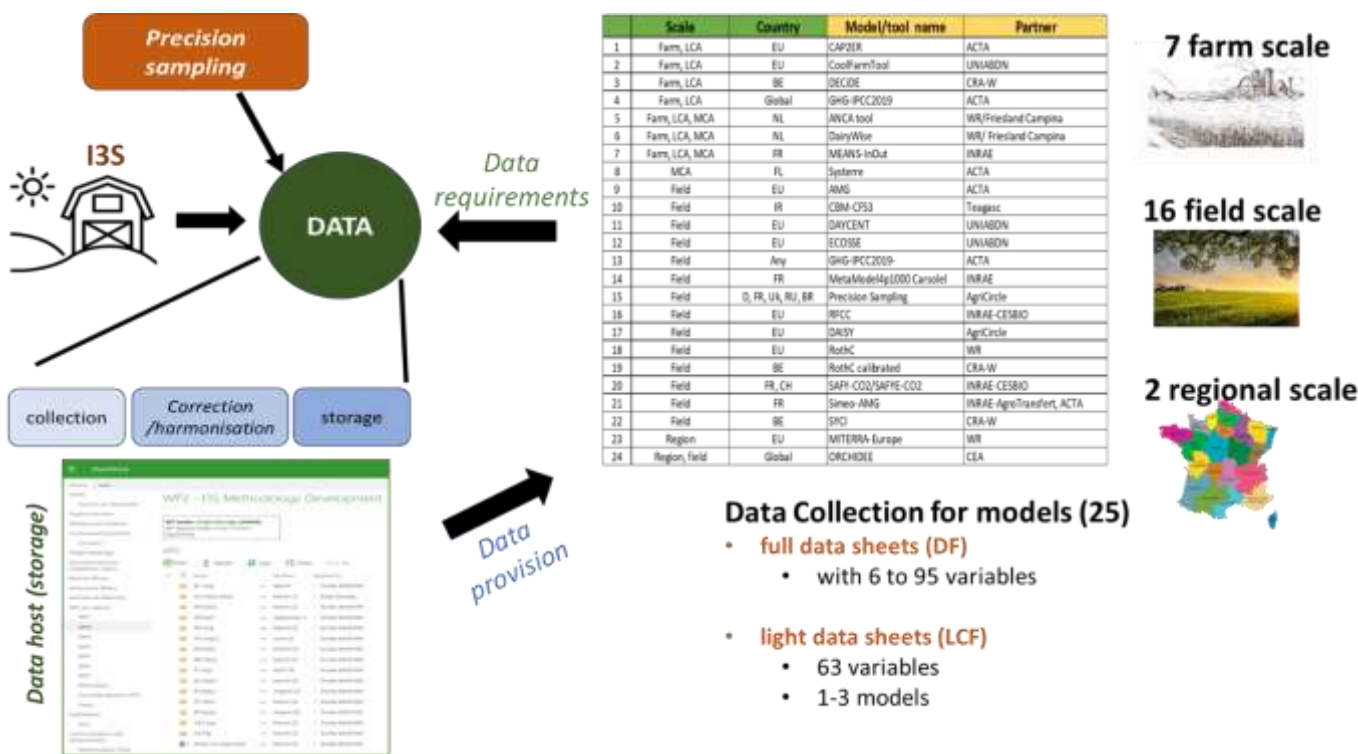


Figure 4: Scheme on data requirements for the different models and tools, with data sheets and workflow of data sheets and precision soil sampling (3.3.2).

This resulted in compromises, asking on one hand still for a long list of data, but accepting data gaps which makes continues modelling or the analysis of crop rotation more challenging or impossible. On the other hand, the I3S managers and their team and colleagues hand a lot of work to do to collect the data and provide them to WP2 to make them available for the modellers though the data host (Sharepoint folders) after data cleaning and harmonisation. Data collection indicated that data provision is difficult task for farmers, as the result of Cereal DF farms showed, 46±7 % of data was filled by the 5 crop I3S, whereas 41±9 % was not filled and 7±1 % of the variable sheet did not correspond to the crop farms.

Filled data, covered the most important categories including field size, details on crop production, residue management, cover crops, soil parameters and soil work. The missing data pertain soil amendments,

irrigation, organic fertilisation. The data for two years were requested to have a baseline and a previous year (within a 3- to 6-year period before the baseline, ideally 5 years before). The year in the past would allow model calibration and evaluation for trends (see MS 3: Compile baseline of the I3S performance).

Several data sets included gaps and the provided data differed in format, unit, clarity, etc. The data were unified to a certain level, but a complete unification of the data was due to the amount of information not possible.

3.3.2. Precision Sampling

Agricultural lands are spatially heterogeneous environments by their nature. Traditional soil sampling methods often treat a field as a homogeneous parcel, collecting samples from a fixed grid or random locations. This one-size-fits-all approach fails to capture the inherent heterogeneity of soil characteristics that exist within a field. Precision sampling revolutionizes soil mapping by using various strategies and techniques to collect targeted samples from specific locations within a field. This approach focuses on areas with high variability, leading to a more accurate representation of the spatial distribution of soil characteristics, such as texture, pH, nutrient levels, and organic matter content. This is particularly beneficial for fields with readily observable variability, such as differences in slope or vegetation cover. Furthermore, management zone sampling recognizes that past management practices and inherent soil properties can lead to distinct zones within a field with predictable variations in soil characteristics. By combining knowledge of past practices with tools like aerial imagery or yield maps, samples can be strategically collected from representative areas within each zone.

The benefits of precision sampling for soil mapping are numerous. Increased sampling density and targeting areas of variability lead to more accurate and detailed soil maps. These maps provide a more complete picture of the field's soil characteristics, which is crucial for informed decision-making. Furthermore, by focusing on areas of potential variability, precision sampling allows for more efficient use of resources like time, sampling, and laboratory analysis costs.

Detailed soil maps generated through precision sampling enable the development of site-specific management practices. For instance, variable-rate fertilizer applications can be tailored to match the specific nutrient needs of different zones within a field, optimizing resource use and crop production. By optimizing nutrient application and reducing over-fertilization, precision sampling can contribute to improved environmental sustainability by minimizing potential nutrient leaching and pollution risks.

3.3.2.1. Precision sampling strategy in ClieNFarms

The aim of the Precision Sampling approach developed by AgriCircle is to improve cultivated area management by taking Precision Sampling has been designed to explain such variation by relating it to spectral heterogeneity, which is calculated from the last five year's temporal Sentinel-1 (S1) and Sentinel-2 (S2) data. In this approach, Sentinel-1 provides sensitivity to dielectric properties and roughness, whereas Sentinel-2 provides information on visible and near-infrared spectral signatures. The soil monitoring aim is reached by applying a cloud detection and NDVI filter based on the available S2 data. The dates of the NDVI-filtered S2 images are used in the next step to filter the S1 stack by selecting images that were acquired within ± 5 -day window. Temporally matching S1 and S2 image stacks are handled separately in the dimensional reduction stage. After the dimensionality reduction stage, a three-channel image called a spectral heterogeneity map, was formed using the first two descriptors of the S2 stack, a first and second channel, and the first descriptor of the S1 stack in the third channel. Before the Precision Sampling point decision, the pixel values in the RGB image of the spectral heterogeneity map were projected into a hex code, which then later translated to a unique integer. This prevented the loss of information on the spectral heterogeneity. Lastly, the histogram of the hex map is used to decide the Precision Sampling points by selecting the points that correspond to the minimum, maximum, and every

local extreme (minima and maxima) of the histogram. This allows sampling to be done based on the spectral descriptive locations in the field.

By collecting soil samples from these Precision sampling areas, researchers can obtain ground-truth data to calibrate and validate Daisy and RothC models. The detailed soil information from precision sampling, combined with the spatial coverage of remote sensing data, allows for the creation of highly accurate and informative SOC maps across entire fields.

However, it is important to consider some factors when implementing precision sampling. While precision sampling offers significant benefits, the costs associated with increased sampling density and the potential use of advanced technologies need to be considered. It is crucial to weigh the costs against the potential economic and environmental benefits. Additionally, precision sampling can generate a wealth of data. Having the capacity to effectively manage, analyse, and interpret this data is essential for translating it into actionable insights for soil management.

3.3.2.1. Applied SOC algorithm

Another compelling research is to combine remote sensing and machine learning for mapping soil characteristics. The core concept lies in training models to estimate various soil characteristics across a field or region. These properties can include essential parameters like clay, silt, and sand content, along with crucial chemical indicators like pH, soil organic carbon (SOC), and macro and micronutrient levels. The models used for soil characteristics mapping rely on a rich dataset collected through various ground measurements and existing datasets (Yuzugullu et al; 2024). This data serves as the foundation for the model's learning process. By analyzing these diverse data points, the models establish relationships between measurable factors and the target soil characteristics.

3.3.2.1. Initial results of precision farming

Three I3S farms were selected initially to test the developed approach: Daisy, Roth-C, and ML models developed by AgriCircle to derive soil characteristics. AgriCircle and other partners within the ClieNFarms project collaborated with managers to execute a precision sampling initiative focused on quantifying soil carbon levels in the selected areas. In the following section, we will only start by presenting the first results of the soil characteristics mapping using the ML models developed within AgriCircle and the corresponding SOC stock where precision sampling was performed. Daisy results that need more calibration will be shown initially for the Pig Park North field from the Allerton Farm in the UK Crops I3S data. Other preliminary results will be shown in the appendix, but more refinement and calibration are needed. Roth-C results, which are still under development where further investigation and testing are needed, are not going to be shown at this stage.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

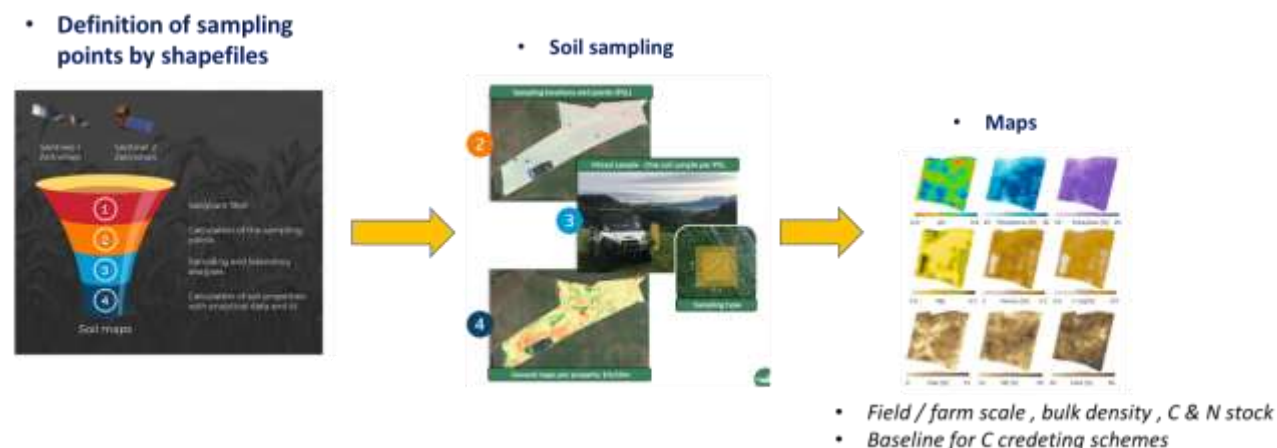


Figure 5: Scheme on precision soil sampling steps

3.3.3.1 Data Collection:

The shape files and Farm/field data were collected by the I3S managers within WP2 (i.e. Figure 5). The soil property estimation is done using a machine learning model trained over more than 30K samples. The model uses Sentinel-1 and Sentinel-2 data, topography, climate, and other features. More detailed information can be found in (Yuzugullu, 2020).

3.3.3.2 Precision Sampling and remote sensing SOC modeling for Pig Park North (UK crops)

In the following sections, we present the outcomes from the precision sampling initiative designed to improve the estimation of soil organic carbon (SOC) stocks for the selected field at Pig Park North (UK crops) using I3S data. At specific sampling locations meticulously selected for their representativeness, measurements of both bulk density and soil organic carbon percentage (SOC) were conducted by the I3S managers. Figure 6 shows the spatial variation of Clay and Bulk density for the Pig Park Field obtained with AgriCircle’s remote sensing-machine learning algorithm. Subsequently, utilizing the data acquired from these precise sampling points, we adjusted the soil maps, which provide detailed information on SOC percentage and the SOC stocks (Figure 7). This pixel-level quantification of SOC stocks represents a significant advancement compared to traditional methods, offering a more comprehensive and spatially accurate assessment of soil carbon storage.

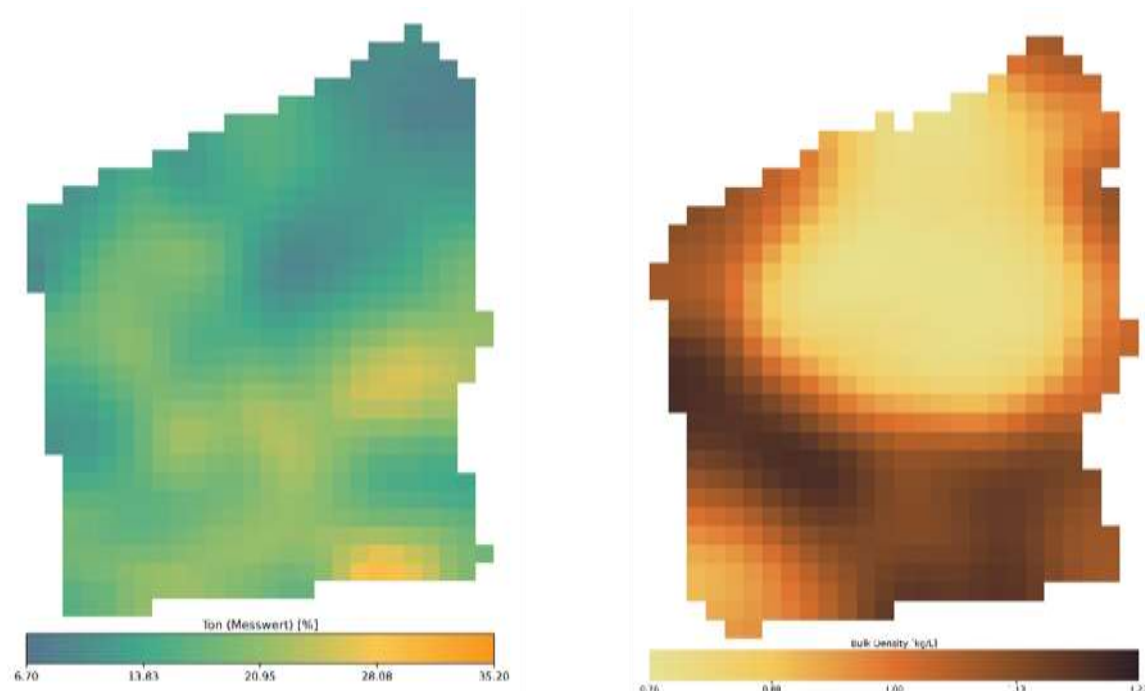


Figure 6: Spatial variation of Clay and Bulk density for the Pig Park Field (UK crops).

Figure 8. depicts the temporal distribution of soil organic carbon (SOC) stocks simulated by DAISY for the 2021-2022 season. It is noteworthy that conducting SOC simulations with DAISY necessitates an extended timeframe to ensure model stability. Additionally, parametrization emerges as a crucial step in the process, demanding meticulous adjustment to align with SOC measurements accurately.

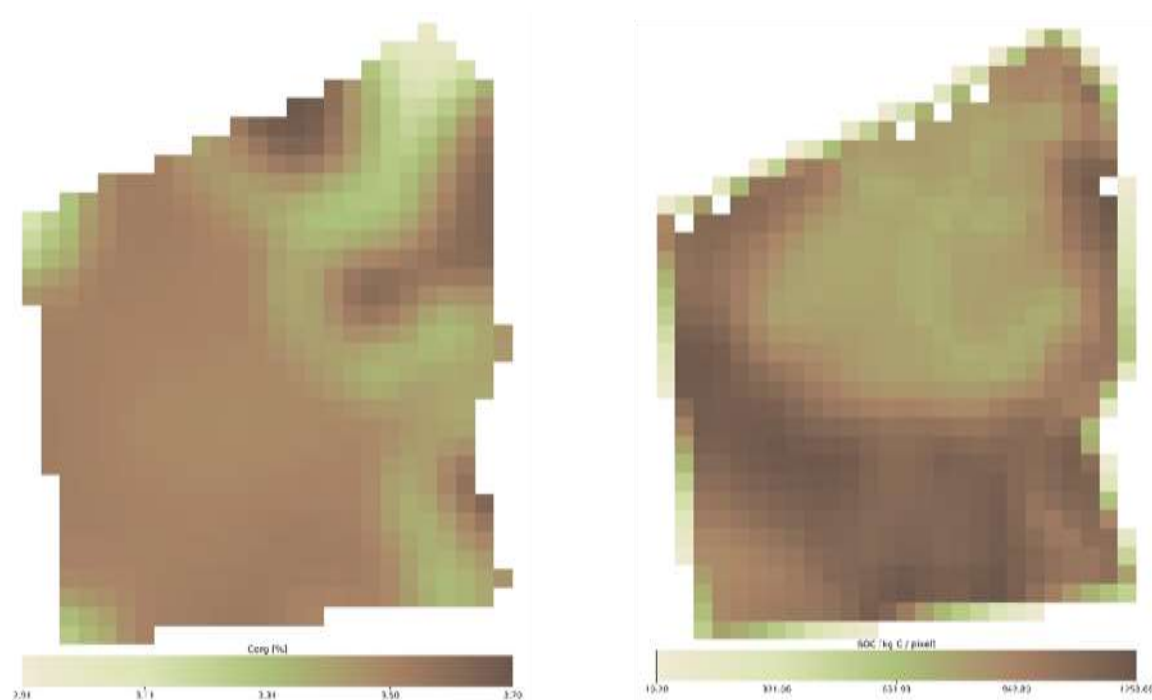


Figure 7: Spatial variation of C_{org} (%) and SOC stocks for the Pig Park Field (UK crops)

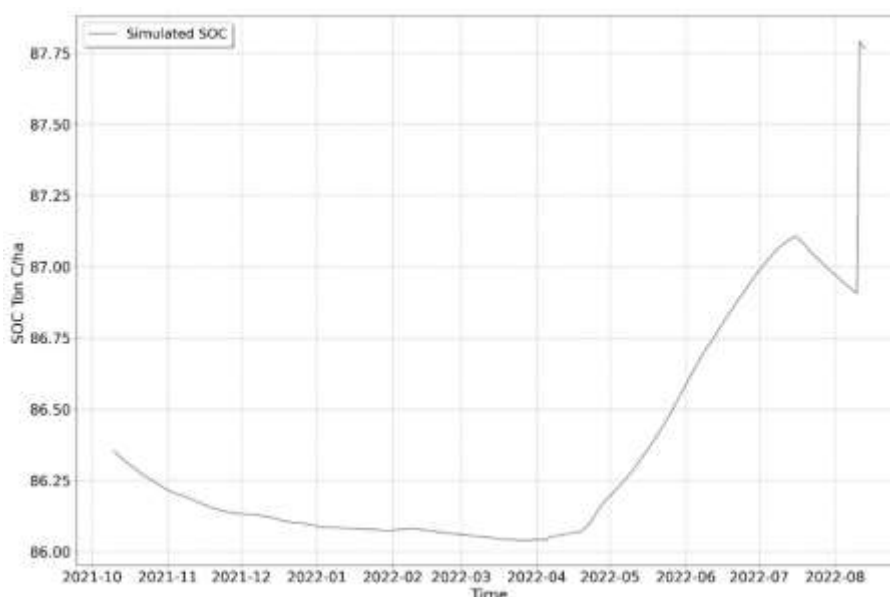


Figure 8: Temporal distribution of the SOC stocks simulated by DAISY for the 2021-2022 season

3.3.3. Parameterisation and use of the different models and tools

To have a reference tool, the Cool Farm Tool (CFT) was chosen among various possibilities. It is developed for global application and includes almost all livestock and crop options required. The CFT was used as the standard tool in ClieNFarms. This approach allows the use of a single tool to simulate each of the I3S demonstration (DF) and lead commercial (LCF) farms in the project, providing the necessary data.

However, the application in ClieNFarms revealed that CFT is not satisfactory for pig farms and olive orchards. Although these categories are included (pigs as special category and olives in form of orchards), the Cool Farm Tool is insufficient for accurately simulating these farms.

Due to the capacities and time constraints, only the Cool Farm Tool was used to simulate all farms (except the pig farms), while the other models and tools were applied on selected farms, with the selection determined by modellers using each a specific model or tool.

Likewise, the parameterisation was left to the modellers, as each model requires a model specific format. In some case categories or preselected options are used. In consequence, except the Cool Farm Tool, all models and tools were applied by experts (expert in using this model or tool) or by people who got training or experience on the applied tool. For the Cool Farm Tool a generic introduction of the use of the Cool Farm Tool was provided by the Cool Farm Tool Alliance. Additionally, individual advice on problems was provided by experienced Cool Farm Tool users.

3.3.4. Baseline simulation

3.3.4.1. Setting the baseline

The baseline is the GHG emission balance for the farm under traditional or conventional farming management. A baseline provides the control for a measure of management change to affect a target variable. In the context of ClieNFarms this change is called action to affect less emissions on the farm. A correct baseline would run parallel to a field with the action applied under the same environmental

conditions. As this is an unrealistic scenario for real life applications, the applied baseline is set as the initial state of the farm, rather than using a field or group of livestock parallel to the treatment. Impacts of actions are defined as the difference between the final farm conditions at the end of the project and the baseline.

Using initial conditions as baseline includes the risk of impacts of underlying “natural” trends that are not related to the management change which will affect amplitude of the impacts due to the changes. In the project additional historic data (within the period 3-5 years before the start of the project) were collected to get an estimation for trends. It should be noted that even with these additional data these are only snapshots. For a complete and better analysis, more years are required to cover varying impacts within a crop rotation or consider annual variabilities in yield due to weather changes or impacts of extreme events.

In ClieNFarms the participating farms have taken already steps (changed specific management options) to reduce greenhouse gas emissions. To account for this, the years 2021 or 2022 were used as baseline conditions accepting that some farms are already in the transition towards climate neutral farming. The baseline simulations are also used by WP1 for farm assessment (see Farm Baseline sheets as provided by WP1) to have the farm specific carbon footprint. Details are summarised in milestone MS3.

3.3.4.1. Calculating the baseline

The baseline for achieving climate neutral farming is the farm specific GHG emission balance, which summarises all contributing emissions, which are expressed as CO₂ equivalent. Due to the challenges in directly measuring of all contributing fluxes, the baseline was simulated by using farm-specific data and life cycle assessment (LCA) tools for each farm. The simulations were primarily done by the Cool Farm Tool, and complemented for several farms by additional models or tools. I3S managers partially completed the Cool Farm Tool simulations, while the team from Task 2.2 handled the rest. For some farms the Cool Farm Tool baseline is complemented by calculations of other tools.

Even though the Cool Farm Tool is designed for the use by farmers or other stakeholders, there are some challenges involved in completing the assessments. Although e most farms possessed the necessary data required to complete the assessment, the input might be affected by different interpretations of provided data as the data were provided as diverse categories and in varying units.

Accordingly, the calculation of the baseline was set up as a trial to analyse how realistic a real-life application will be for assessing a farm. A generic introduction for the use of the Cool Farm Tool was provided by WP2 and the Cool Farm Tool Alliance. The Cool Farm Tool was run by I3S managers (or colleagues form the I3S management team) and modellers. All groups were able to complete the assessments, but several groups required help or at least clarification about how to interpret specific management options. Without discussing all details, a real-life application of a tool like the Cool Farm Tool (also the other tools in the project) is realistic, as long as a clear introduction and continuous support is provided. It is beneficial if users will develop some expertise on using the tool.

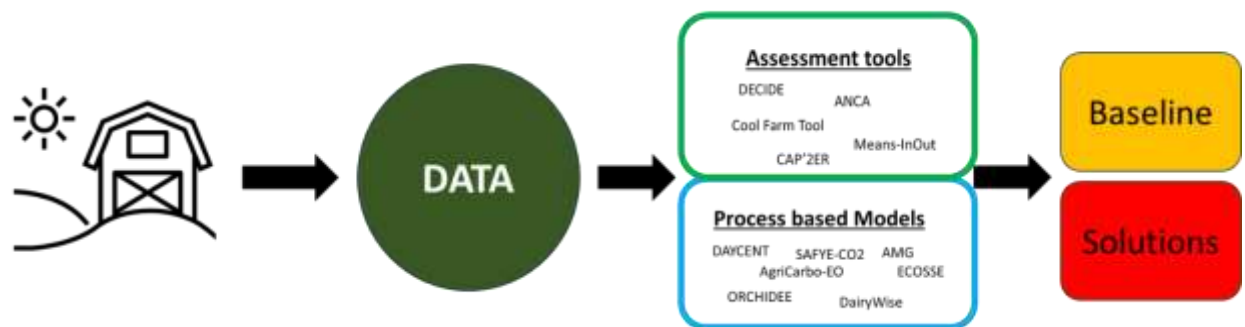


Figure 9: Scheme of workflow of data to modelers and simulations

3.3.4.1. Results of the baseline calculations

The results of the baseline calculations are summarised in a data sheet that is provided for the I3S managers (see also Milestone MS3). It should be noted that only a qualitative and not a quantitative comparison between farms is useful. The simulated emissions are based on farm specific constellations (e.g. farm size, actual stage in the crop rotation), which makes a direct comparison of the absolute emissions impossible. A qualitative comparison is still possible (e.g. a comparison of the hotspots), but this has to be done under the consideration of the farm specific constellation and should not be used to rank farms against each other.

The results are presented using three different units: 1.) absolute emissions per farm, 2.) emissions per unit product, 3.) emissions per area. Each of the unit is relevant for a specific stakeholder group and also only a consideration of all three values allows a fair judgement and decision support for strategies to move towards climate neutral farming. Figure 10 shows a relative comparison for normalised emissions using the different units for the demonstration farms in ClieNFarms. This figure shows the largest variability for emissions per area. Farm F7 is an exception due to the focus in the production. The presentation of these results is anonymously to avoid comparing or ranking specific farms.

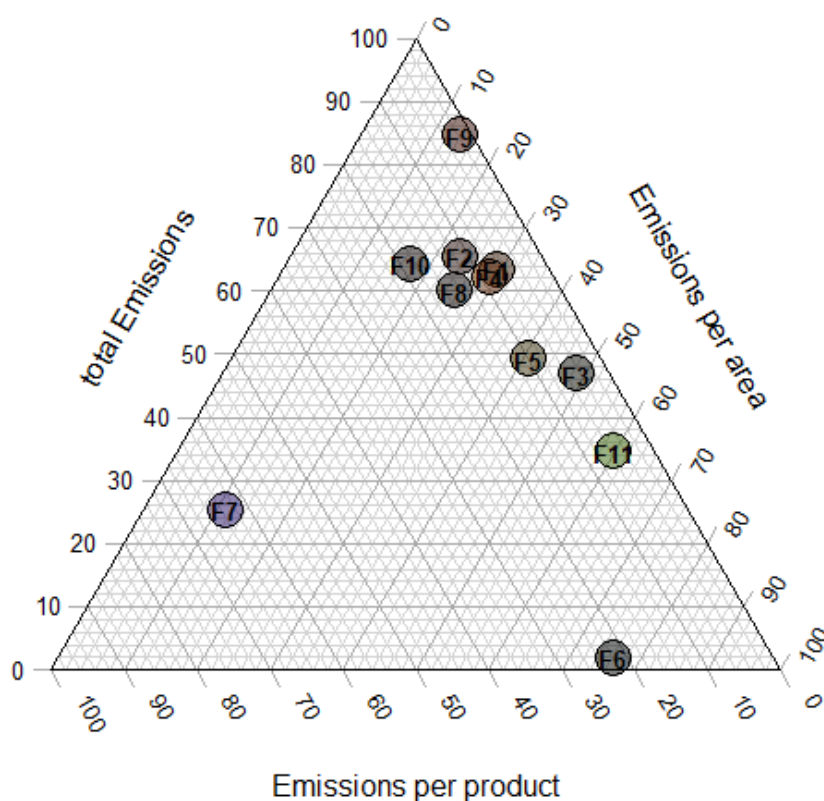


Figure 10: Relative comparison of the normalised (normalised by the maximum value for each category) for the different units against each other. The sum of each normalised emissions for each farm is 100. This means the values indicate for which unit the farm is ranked high or low in relation to the other farms.

In general, for most farms there is a correlation between total emissions on the farm and the emissions per area or per product (Figure 11). However, there are also extreme outsiders that show an extreme difference between the results presented in different units. These differences can be explained by product specific impacts, farm characteristics and specific farm management.

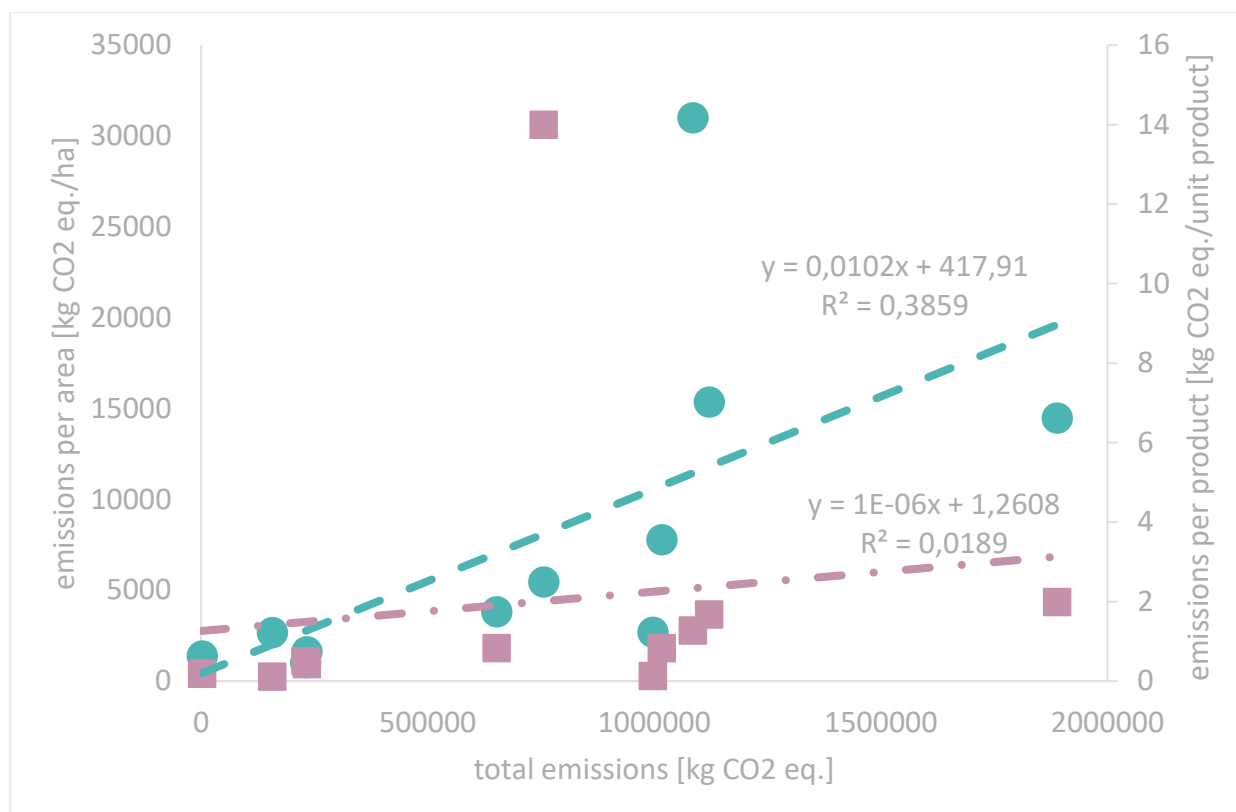


Figure 11: Correlation of the baseline information in emissions per area (green) and emissions per product (red) in comparison with farm specific total emissions. The equations show the result of the linear regressions for each data set.

3.3.5. Simulation of changes in the management to achieve climate neutral farming

Using models and tools to monitor emissions or emission changes is good supporting information, but is not accurate, as it is affected by errors and uncertainties. These errors and uncertainties are not restricted to the model, but also include the use of the model, data aggregation, errors and uncertainty of used data, and more. Therefore, models are useful tools to support decision making, interpolate or extrapolate measurements and complement measurements (i.e. Figure 1). In general, simulating changes of target variables is considered to be more accurate than using models or tools for assessments, as biases and errors affect both the baseline and the simulation of affected actions.

Likewise, it should be separated into two categories: process-based models and assessment tools (i.e. Figure 2). **Assessment tools** are designed for assessing actual conditions and not for monitoring changes. Obviously, in a second assessment planned or applied action can be changed in the setting and the difference to the baseline can be used as value for the change. This approach is not working and includes several problems and error sources. In general, the impact would be the same for all farms under similar conditions, as the used factors are static and only modified and adapted to a limited set of conditions (e.g. climate zones). Additionally, the assessment tools only take a snapshot of one year. Impacts of annual climate or management variability (e.g. different stages in the crop rotation) are not considered, which will affect the result without indicating actual changes that are relevant for climate neutral farming. Monitoring requires the consideration of environmental changes as well to include dynamic conditions to simulate changes that are associated with the changes of the action and provide robust results.

Process-based models provide the option of continuous and dynamic modelling. Therefore, they are more suitable for monitoring changes in the GHG emissions. As outlined above the quality of the simulation results depend on the availability and quality of data to run the model.

Despite the constraints and limitations, process-based models offer several advantages and can provide valuable additional information for GHG emission monitoring. While the data issue has been already discussed, this section addresses the use of maps and spatial data sets. Whether for spatial modelling or for field/farm specific modelling, the use of spatial data sets and maps can supply necessary data to avoid additional measurements. Soil maps, land use and land cover maps and spatial climate data sets are available from different sources. The use of these data sets is critical, as the sources for information are diverse, key aspects are not included (e.g. land use specific SOC values) and data aggregation affects the data sets. Using spatial climate data is acceptable but also requires care for mountain terrains. Soil maps are based on data and interpolation, which partly includes data from a long period without including changes. However, the major global soil data sets (SoilsGrid and HWSD) are continuously improved and upgraded to address these limitations. This makes them a sufficient source for regional scales, but it is still critical to use these data for field or farm simulations.

A strong **advantage for using process-based models** is the option to use an actual baseline rather than a before and after comparison. The simulations for the baseline and action-based scenario can run parallel which allows the detection of underlying natural trends due to potential changes in the baseline run. The continuous simulation provided continuous (in most cases daily or monthly) data. These data improve the analysis as the data show seasonal differences and impacts of extreme events. This is or can be crucial for risk management and account for unexpected losses e.g. of SOC due to extreme events, which could be relevant for insurances.

Beside all the technical analysis, it is crucial **who is using the model**.

- In general models can be used by **model experts or non-experts**. However, an understanding of the models as well as of the used data is crucial to achieve the best possible results.
- All tools and models require a professional introduction.
- While several farm tools are developed for the use of farmers, this application is a good basis for informed decisions, but not good enough for assessments or for monitoring GHG emissions changes as basis for subsidies or certificate trading.
- This is not due to the quality of the parameterisation of the tool or model, but the consistency of the results, as terminology and available options can affect diverse parameterisation of the model or tool.
- The use of models by modelling experts can also affect the result (Albanito et al., 2022), which means clear protocols are required and models clearly identified if modelling is used to support GHG emission assessments.

3.4. Model results

This section shows initial results to show the different applications and highlight advantages and disadvantages on concrete examples. The here presented results show how models can be used to support climate neutral farming. **A detailed presentation and analysis of the model results will be provided in deliverable D2.4.**

It should be noted that results are provided as farm emissions and field specific emissions. This is due to the use of the models, but also for enable a more detailed analysis on specific fields.

3.4.1. Results for farms with crop production

This section focuses on the simulation of the GHG balance for croplands. Even though the focus is on cropland farms, livestock or mixed farms are also provided data for cropland management. These data were used for simulations which provides an option to compare results with the crop simulation routines of livestock focussed tools.

3.4.1.1. Cool Farm Tool

The first example shows the results for an olive farm (Figure 12). Crop residues are indicated as the most relevant source for GHG emissions in the calculation. This is correct for the GHG emissions, but the contribution of soil carbon sequestration is only represented in a simplified approach, which is in this case based on tree crops, but not specifically on olives. The increased emissions will be partly or completely offset by long term carbon storage in the soil. As Figure 6 shows, the impact of management (here it is the pruning) shows only a minor impact on the system, while the literature indicates that pruning should show a net increase of carbon in the soil.

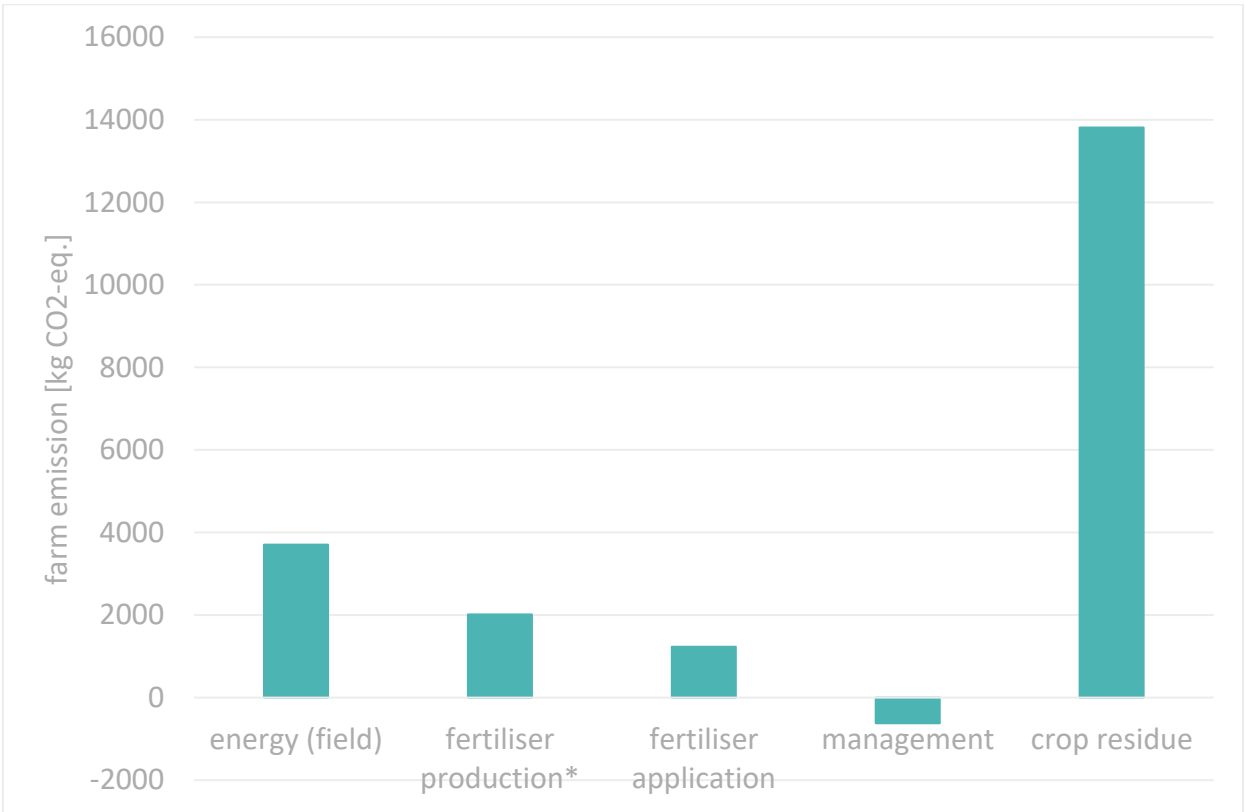


Figure 12: Results of the Cool Farm Tool for an olive farm.

Emissions can be provided as total emissions (e.g. per farm), emissions per area or emissions per product. Each unit includes some additional information and is relevant for different analyses (see below). Figure 13 shows results that are simulated for the same field, under the same management, but achieving varying yields over a 10 year period. There are relevant differences over the years, while the total emissions and emissions per area stay the same. Emissions per product is a crucial unit for production

lanes and as contribution to a processes food product. Picking a single year might not provide sufficient information to have a robust value for a product based footprint. Further, climate change might affect the footprint over time. The here presented results are additionally affected by crop rotations. While the model assumes the same field, the actual yields are achieved on different fields. Small differences in the soil characteristic are not provided as data and is only considered to a limited range by the Cool Farm Tool.

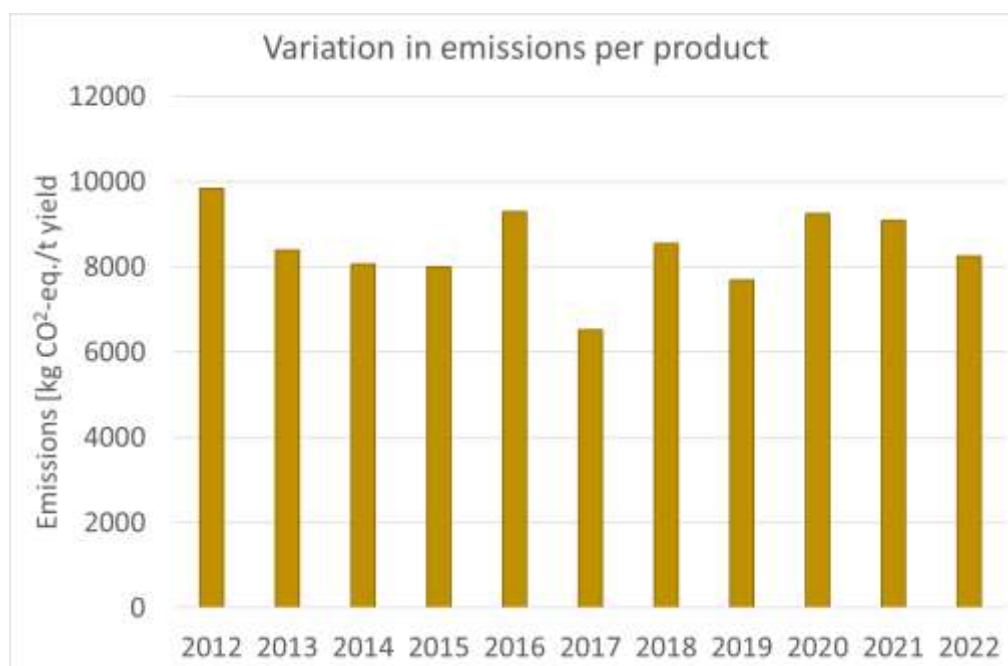


Figure 13: Yield specific emission footprint for one crop on the same farm but for different yields for the period 2012-2022.

3.4.1.1. Means InOut

MEANS InOut v 4.4 was used to assess pollutant emissions, resource use and life cycle assessment indicators of two arable (Italy and UK) and two dairy farms (Germany and France). With the life cycle inventories created in Means InOut, in combination with Simapro, we performed a contribution analysis, identifying the main contributors of GHG emissions within each farm. Here we present results for the climate change impact (Figure 14).

For crops grown under both organic (Germany) and conventional (other regions) farming systems, organic production generally showed lower greenhouse gas (GHG) emissions compared to conventional methods. Notably, the industrial tomato farm exhibited the highest emissions per hectare, primarily due to its irrigation system powered by natural gas and diesel-fuelled pumps, and the use of greenhouses for seedling production, despite cultivating tomatoes in open fields. Direct emissions, including nitrogen dynamics from crop residue decomposition, mineral and organic fertilizer application, nitrification, denitrification processes, and CO₂ emissions from liming, accounted for the largest proportion of total emissions across all farms.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

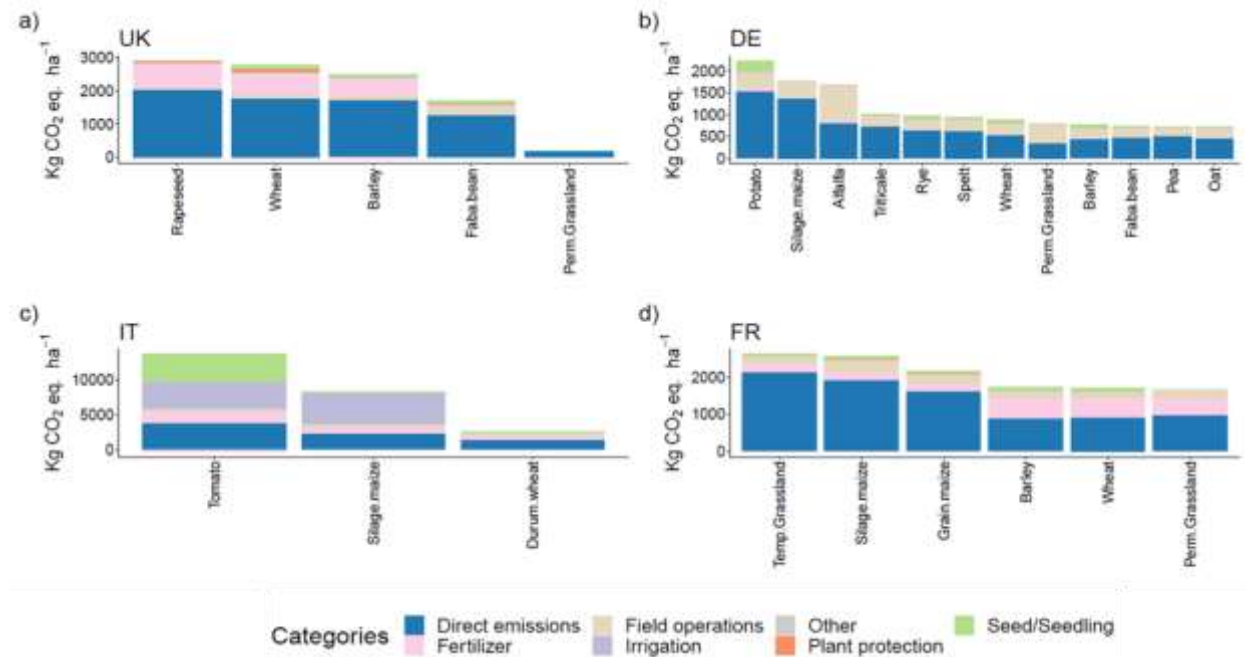


Figure 14: Emissions of GHG per category and crop produced at the two arable farms, a) United Kingdom (UK) and c) Italy (IT) and the effects of crop production at the two dairy farms, b) Germany (DE) and d) France (FR). Data represented in kilograms of CO₂ equivalent per ha. The category “other” represents processes that contribute with less than 1% of the emissions.

3.4.1.1. SAFYE-CO₂+AMG in AgriCarbon-EO

In ClieNFarms, the SAFYE-CO₂ crop model focuses on implementing biomass inputs (crops and cover crops) into the AMG soil model, both being embedded in the AgriCarbon-EO process chain (Wijmer et al 2024). The workflow encompasses everything from the ingestion of input data (e.g. remote sensing data, weather data), the production of GLAI times series along with their uncertainties, and the assimilation of the GLAI into the SAFYE-CO₂ model. It also involves creating maps for each variable of interest with their associated uncertainties, and inputting biomass data into the AMG soil model.

Typically for the Label Bas Carbone, the carbon input of the soil model is based on average yield data at plot or even farm level. In ClieNFarms we aimed to use, high resolution biomass maps generated by SAFYE-CO₂ to compute the carbon input for the soil model. This approach enables consideration of the spatial heterogeneity of vegetation within each plot and aims to evaluate the impact of high-resolution carbon input data on the accuracy of soil model estimates.

The upgraded model was tested for the IT -crop. comprising 5 fields, all divided in two plots with contrasting practices: one part with conventional practices (straw export, bare soil between two main crops) and one with additional organic matter incorporated to the soil (through straw incorporation, cover crop between two main crops and digestate application).

The crop rotation between 2021 and 2024 is: tomato, wheat, silage maize and tomato. For the conventional plot, the soil is bare between each of these crops, but on the other treatment, the plot was covered by white mustard between wheat and maize, and with a mixed cover crop between maize and tomato.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

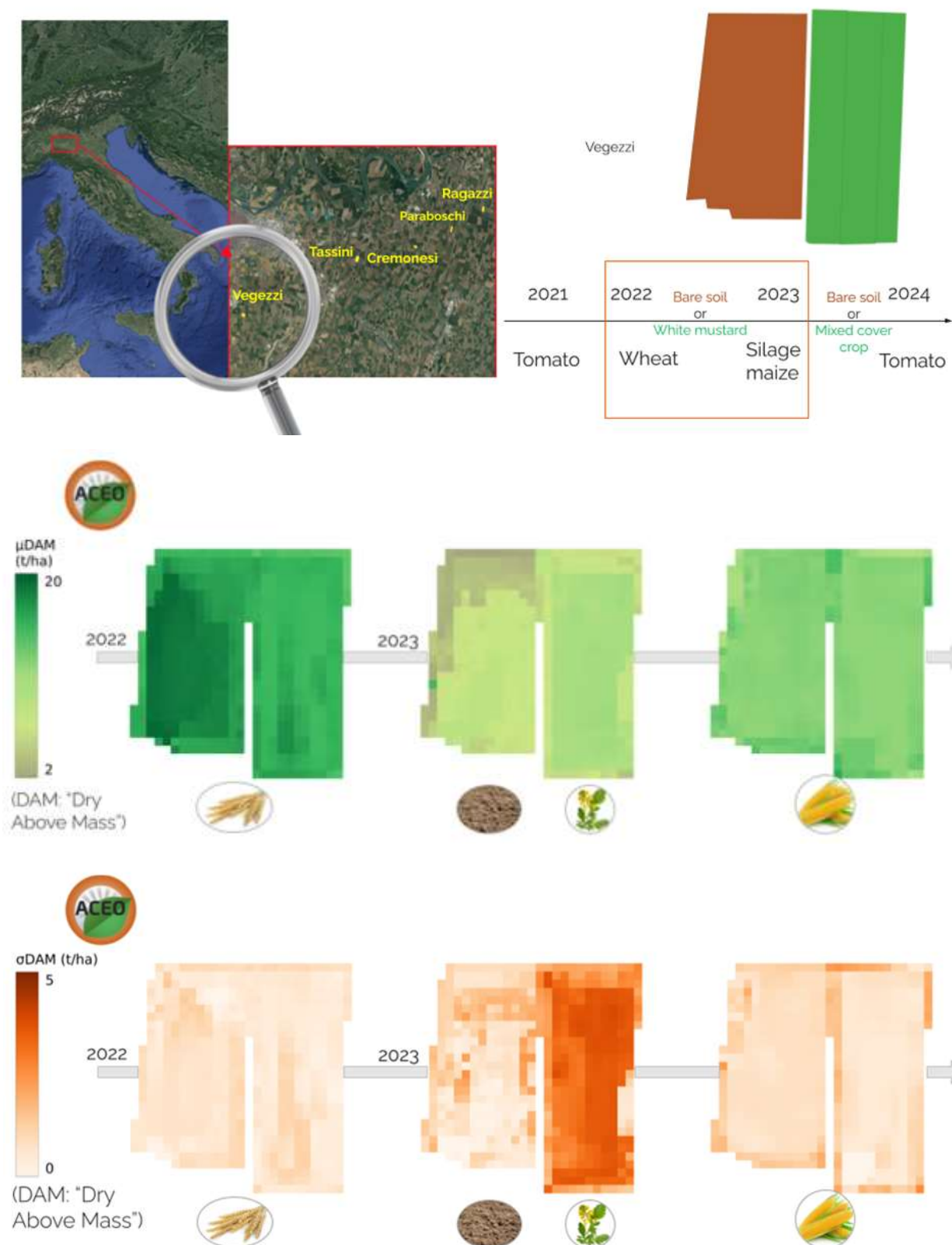
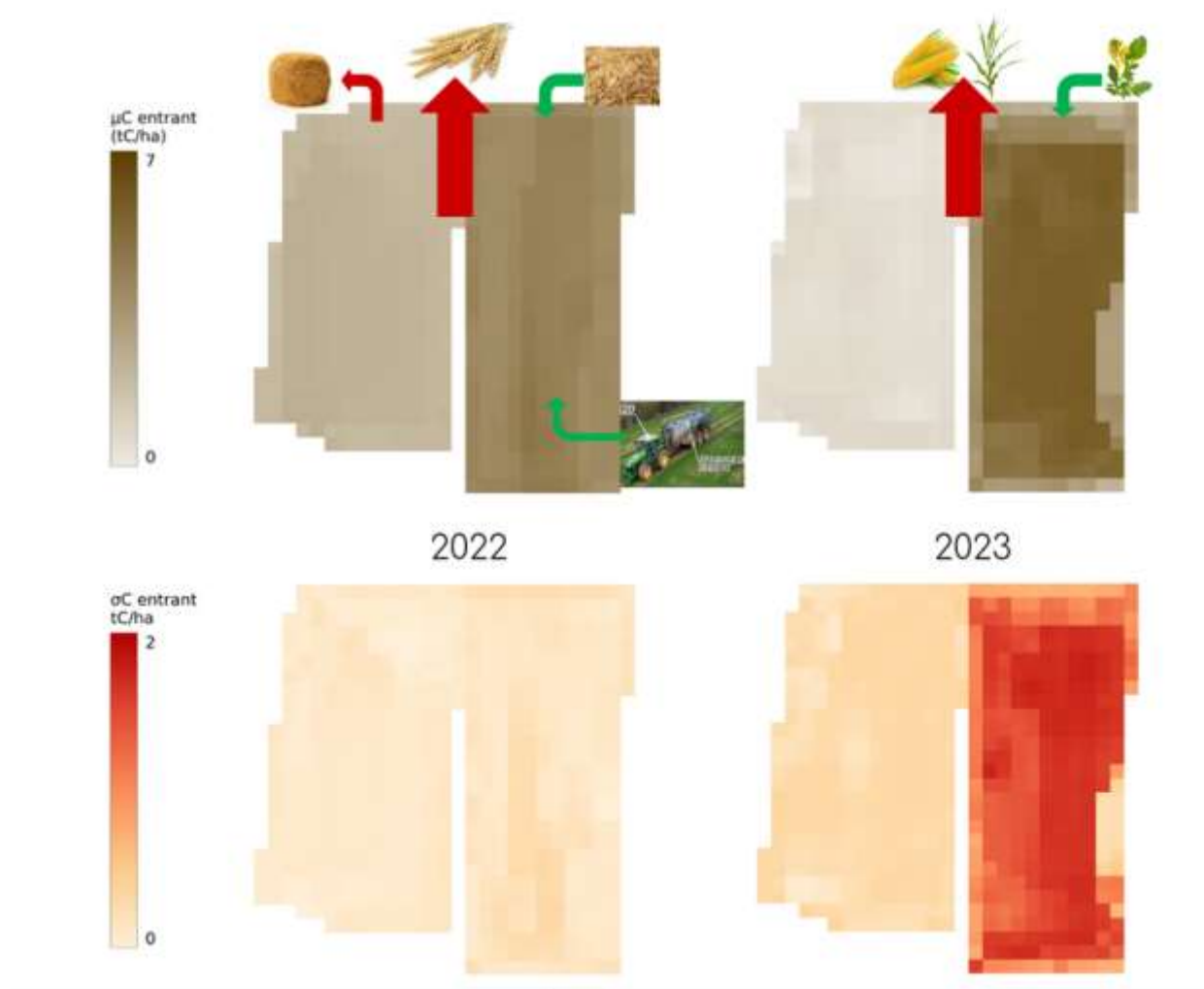


Figure 15: Italian I3S crop rotation (green) with bare soil (orange) and simulation of dry above ground biomass produce by SAFYE-CO2 for wheat, white mustard and silage maize start and end at the end of crop rotation cycle.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

The analysis indicates that by understanding farmer management practices (such as organic amendments and straw management), the total carbon inputs for the soil model can be derived from the total dry biomass estimated by the crop model (excluding yield) plus organic amendments. To achieve this, we have adapted the equations originally proposed by Bolinder et al. (2007) to directly incorporate total biomass instead of just yield. The biomass maps enable computation of spatial variations in carbon input within the plot at a 10-meter resolution.



D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

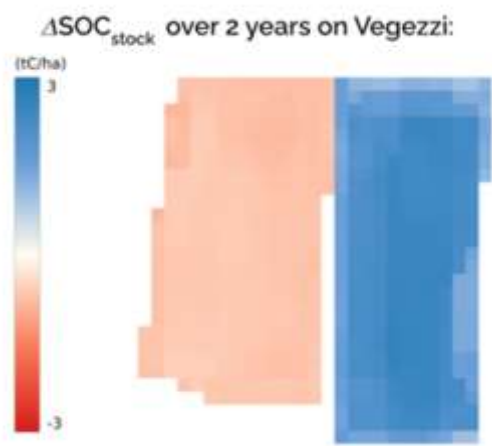


Figure 16: Carbon inputs maps and their associated uncertainties derived from SAFYE-CO2 biomass and activity data., and soil organic carbon stock changes estimated by coupling SAFYE-CO2 and AMG over two cropping years.

Based on the carbon input maps, the AMG model was executed to assess the Soil Organic Carbon stocks changes (ΔSOC_{Stock}) over two years across plots with contrasting practices. The results highlight significant differences in the SOC stock changes: The soil of the conventional plot is losing carbon whereas the one with an additional C input is accumulating organic carbon up to 3 tC/ha.

The output of the five fields are presented together in the figure 17 below. No spatial aggregation is applied meaning that the information of ΔSOC_{Stock} is at pixel level.

The bimodal distribution is consistent with the IT-Crop I3S results and shows the effect of the two contrasting practices on the ΔSOC stock changes over all fields. One part of the pixels is losing carbon (conventional plots) and the other one is accumulating organic carbon in the soil.

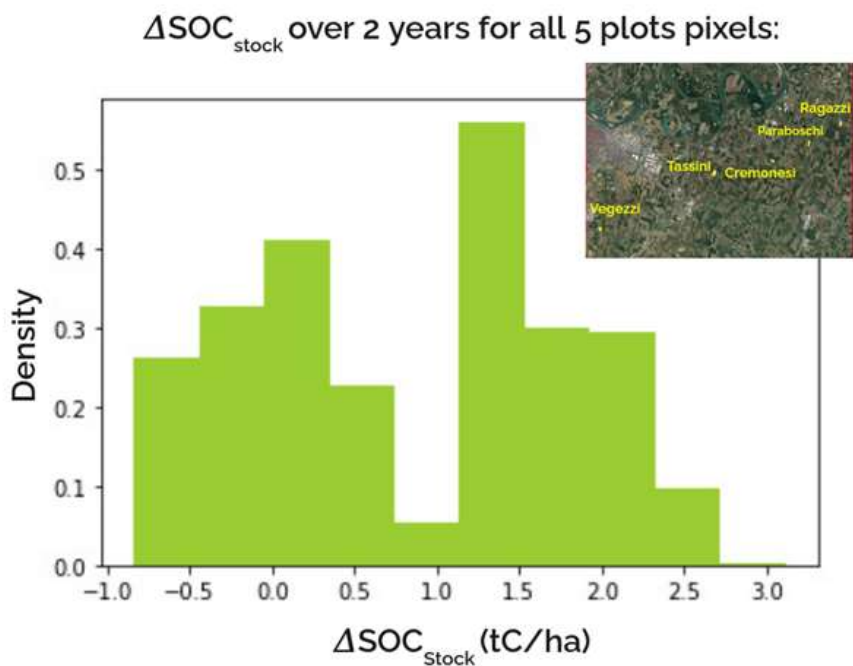


Figure 17: Soil organic carbon stock changes estimated by coupling SAFYE-CO2 and AMG over two years for the five fields of I3S Italian crop system.

3.4.1.1. DAYCENT

DAYCENT is a process-based biogeochemical model or the Tier 3 category. It simulates carbon and nitrogen dynamics for daily timesteps and it can consider all management options on the field. This requires detailed information, including soil data (soil texture, bulk density, and more) and weather data (daily resolution). The parameters for the different crops are provided by the DAYCENT developers or studies that present the parameters in literature. For site specific application of the model a calibration is suggested, but this would require more data. In ClieNFarms, the data provided for the farms is often limited to one, maximum two years, which makes runs with DAYCENT difficult. One I3S provided for the demonstration farm a longer time series and allowed a more detailed analysis. The model was still not calibrated, but the most appropriate parameter sets were picked, using the yield data for evaluation. Figure 18 shows a good fit for all the simulated and observed yields.

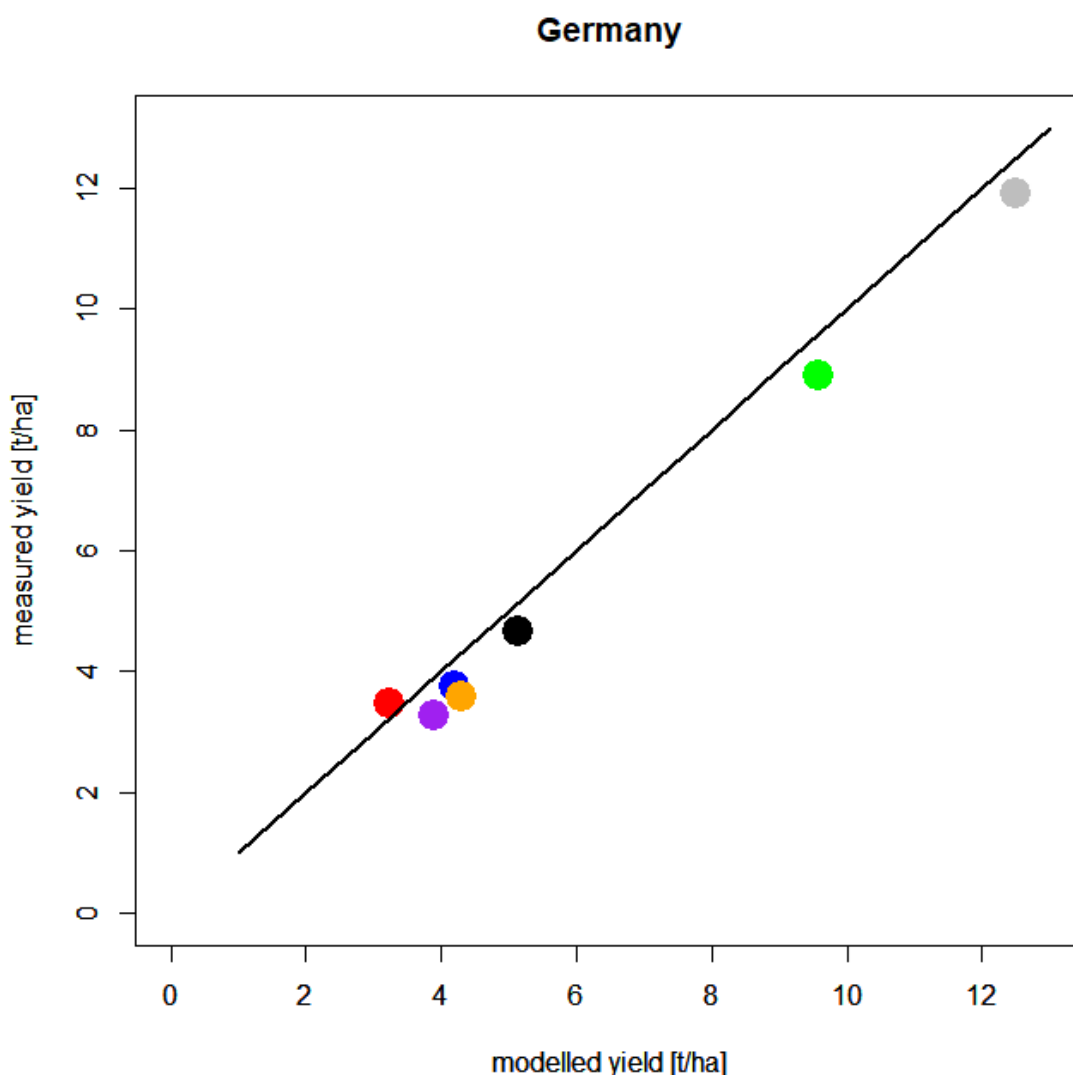


Figure 18: Evaluation of simulated and observed yield for maize (grey), alfalfa (green), winter wheat (black), oats (blue), rye (orange), spring barley (red) and spring wheat (purple) with the black 1:1 line.

The advantage of process-based models is the continuous simulation, which also allows to consider impacts of previous crops and weather impacts, which is important for crop rotations or to consider extreme events or climate change impacts. Most important, SOC changes are only have an impact over longer periods and require therefore continuous simulations, as some effects will affect changes in the following year or impacts might be offset by climate extremes. Figure 19 shows the development for a complete crop rotation on the selected demonstration farm.

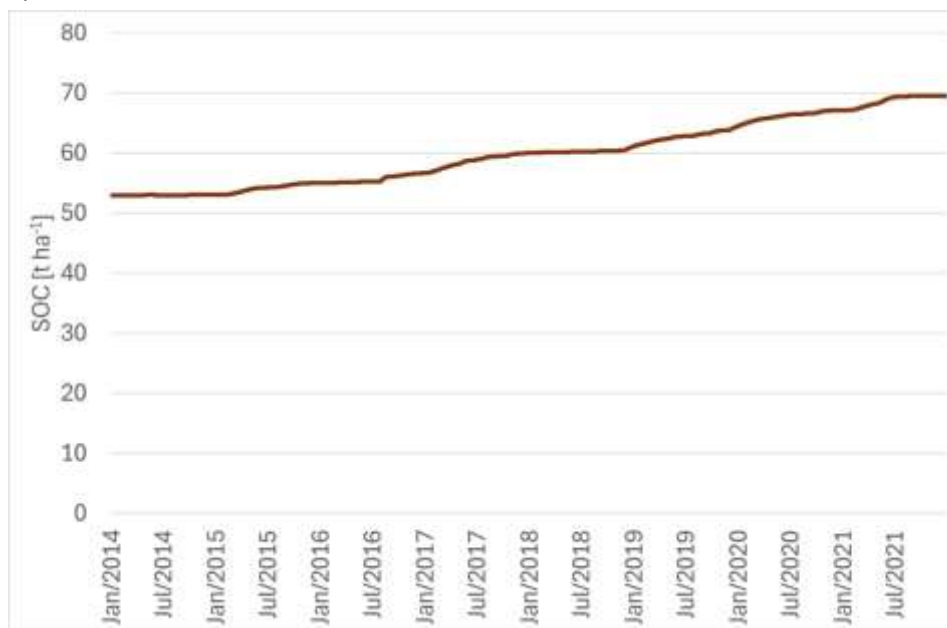


Figure 19: The soil organic carbon development during one crop rotation cycle from 2014 – 2021.

3.4.1.1. ECOSSE

This model will be used to provide data for the Portuguese farm that produces olives. As the focus was on the use of the Cool Farm Tool to provide the standard baseline, this work will start later in the project. This is according to the expected schedule for this model.

3.4.1.1. ORCHIDEE-CROP

ORCHIDEE-CROP was applied for winter wheat fields at 4 farms in Europe. The selection of fields were based on the availability of information on field locations and field sizes exceeding 1ha - a requirement for assimilating satellite observations. ORCHIDEE-CROP shows some skill in predicting biomass yields, but fails to capture variations among farms (Figure 20) and within a farm (Figure 20a). This is expected, as neither different cultivars of winter wheat (Yang Su et al, prep), nor management practices with the exception of N fertilisation & harvest are resolved in ORCHIDEE-CROP. As a consequence biomass yields predicted by ORCHIDEE-CROP primarily depend on climatic conditions and to a lesser extent soil texture which controls spatial variations in soil hydraulic properties in the model.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

ORCHIDEE-CROP simulates surface albedo dynamics which show poor to average performance (depending on the location) compared to observations from sentinel 2 (Figure 21). While simulated surface albedo matches observed albedo when crops reach peak leaf area index, simulations deviate from observations during early growing stage, after crop maturity is reached, and during fallow periods. This is expected as a time-invariant crop albedo, and bare soil albedo product on monthly timescale which fails to reproduce bare soil albedo fluctuation due to soil wetness. In addition, the impact of crop residues is not resolved.

Based on these results, a version of ORCHIDEE-CROP is in development which addresses these deficiencies by resolving increase in crop albedo after maturity is reached, the effect of crop residues, and replacing the coarse scale MODIS background albedo by a new product based on high resolution sentinel 2 product and resolving effects of soil moisture on soil albedo (Yu et al in prep).

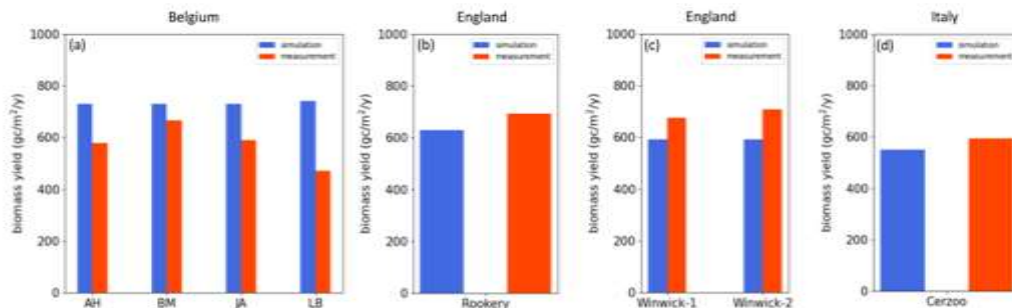


Figure 20: Biomass yields of winter wheat fields for 4 farms in Europe simulated by the land surface model ORCHIDEE (blue) in comparison with observed yields provided by farm records.

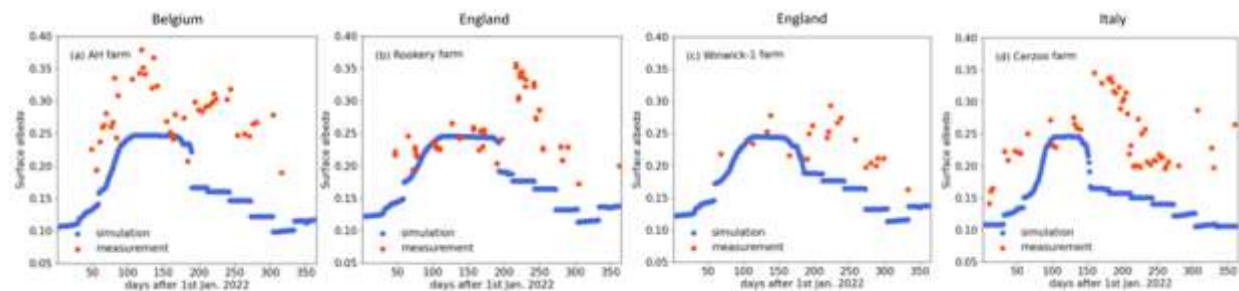


Figure 21: Daily surface albedo of winter wheat fields at 4 farms simulated by the land surface model ORCHIDEE-CROP (blue) in comparison with satellite (sentinel 2) product of surface albedo.

3.4.1.1. DECIDE

Preliminary results of DECIDE show a comparison between Belgian and French crop simulations (Table 4). The results show have the amount of GHGE for one farm compared to the other. This result does not indicate better or worse management but is due to the farm structure and specific sectors. DECIDE is able to also provide information about the NH₃ emissions, beside the GHG balance on the farm.

Table 4: Preliminary results of DECIDE for the cropland simulations of a French (2017) and a Belgian (2021) cropland farm.

Impact categories	level of assessment	unit	Demonstration farms	
			FR_crop 2017	BE_crop2021
GHG	farm	kg eqCO ₂ /Ha UAA	9260	4884
ENERGY		MJ/Ha UAA	323804	11715
NH ₃		kg NH ₃ /Ha UAA	0.4	6.2
	workshop			
GHG		kg eqCO ₂ /Ha of SA	9260	4884
		kg eqCO ₂ /FU	-	-
ENERGY		MJ/Ha SA	323804	11715
		MJ/FU	-	-
NH ₃		kg NH ₃ /Ha SA	0.4	6.2
	Product			
GHG		kg eqCO ₂ /FU	-	-
ENERGY		MJ/FU	-	-
NH ₃			-	-

3.4.2. Results for dairy and livestock farms

The major farm type in the ClieNFarms project are dairy farms. Several of the used tools are specifically developed for dairy farming, while other tools (e.g. the Cool Farm Tool) are generic tools that can simulate also dairy farms. Depending on the tool, the crop imported to the farm or produced of the farm are included in the balance or they are not.

3.4.2.1. Cool Farm Tool

The results for a dairy farm show the total emissions for the farm, presented for the contributions of the different separated sectors on the farm. This analysis enables the identification of the hotspots. Even though, the hotspots are known, the relation to the other contributing sectors provides the knowledge basis to estimate the impact selected mitigation options will have in relation to the entire farm.

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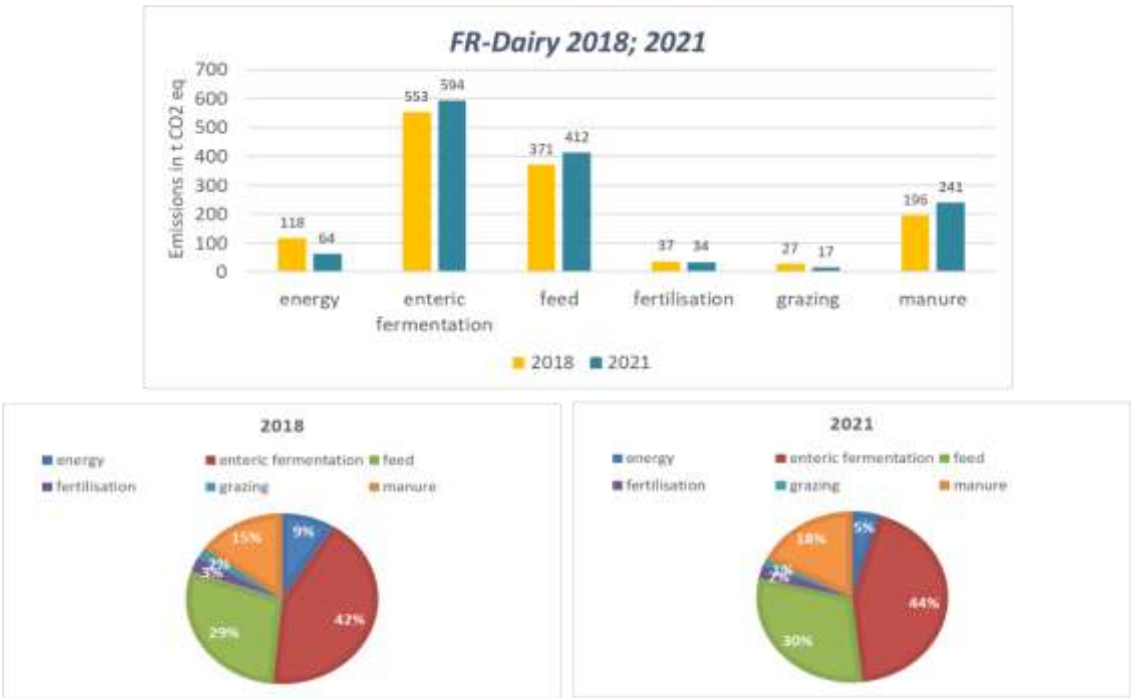


Figure 22: Cool Farm Tool results of a FR demonstration dairy farm separated by categories.

3.4.2.1. CAP'2ER

CAP'2ER offers a large number of results for advisors and farmers. These results include both environmental and technical indicators. The values provided here are only the main environmental results of the assessments. These results are expressed in 3 functional units. At the farm level the functional unit is the ha of UAA, at the production unit level, the functional unit is the ha of UAA used by the production unit, at the product level the functional unit is the litter fat and protein corrected milk.

Table 5: Results of CAP'2ER for three different dairy farms (Franc (FR), Germany (DE), Ireland (IRE)) at three different years (2018, 2021, 2022).

Impact categories	Level of assessment	Unit	Demonstration farms			
			FR_Dairy_2018	FR_Dairy_2021	DE_Dairy_2021	IRE_Dairy_2022
GHG	FARM	kgeqCO2/Ha UAA	8847	7758	5184	16366
ENERGY		MJ/ha UAA	25507	17501	13943	38999
GHG	UNIT	kgeqCO2/Ha UAA	9310	8216	6245	16366
ENERGY		MJ/ha UAA	26349	18062	15242	38999
GHG	PRODUCT	kgeqCO2/L FPCM	0,97	0,83	0,86	0,98
ENERGY		MJ/ L FPCM	2,73	1,82	2,11	2,34

3.4.2.1. DECIDE

First results of three dairy farms (FR, DE & IRE, with one for two years) show a wide range of emissions per area. However, it should be noted that the emissions per product show a different relation between the farms. A direct comparison of the results between the farms is not possible without including a wider view on several additional parameters and conditions, as the presented values are affected by farm

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

specific conditions. As simple analysis of these values, would penalise smaller farms and organic farms. The quality of the product is not reflected by the emission values. Other aspects like animal welfare or biodiversity are also not included in the emission numbers.

Table 6:
Results of
DECIDE for three
different dairy
farms and two
different years.

Impact categories	level of assessment	unit	Demonstration farms			
			FR_dairy 2018	FR_dairy2 2021	DE_dairy 2021	IRE_dairy_ 2018
GHG	farm	kg eqCO ₂ /Ha				
		UAA	8859	7563	4224	19452
		MJ/Ha UAA	24946	16867	13883	37030
NH ₃	workshop	kg NH ₃ /Ha				
		UAA	52.2	31.3	31.3	75.1
		kg eqCO ₂ /Ha of SA	8710	7569	4605	19431
ENERGY	Product	kg eqCO ₂ /FU	1.15	0.91	0.74	1.22
		MJ/Ha SA	24458	17348	16389	37985
		MJ/FU	3.24	2.09	2.65	2.38
NH ₃	Product	kg NH ₃ /Ha SA	0.007	0.004	0.006	0.005
		kg eqCO ₂ /FU	0.88	0.72	0.65	0.99
		MJ/FU	2.47	1.65	2.3	1.94
NH ₃			-	-	-	-

3.4.3. Analysis of the application of the different models and tools in ClieNFarms

While the tools and models were able to simulate the emissions for “standard farms”, there were a couple of farm systems which couldn’t be simulated by any tool or model. With some adaptations or assumptions some farms could be still modelled, but for one this was not possible. Most challenging was the UK pig farm. While the Cool Farm Tool includes pigs as livestock, the data sets and options are too simple for an appropriate assessment.

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Further, there is some additional work ongoing to simulate the Portuguese farms that produce olives. The Cool Farm Tool provides a tree crop routine, but this part is developed on data from apple orchards, lemon tree and other tree crops, but not specifically on olives. While some parameter might be transferrable, in ClieNFarms we worked on providing olive orchard specific models and solutions.

scale	Model		BE Crops	CH Dairy	*ES- Dairy	FR beef	FR Dairy	DE Dairy	IRE dairy	IRE beef	NL Dairy	CH- Dairy	*IT Tomato	FR Crops (SW)	FR Crops (NE)	UK Pigs	UK Crop	* PT Olive	RO Goat	PL Dairy
field	DAYCENT/Ecosse	UK																		
field	\$ SafeCO2	FR																		
field	AMG	FR																		
field	DayCent/RothC	IRE																		
farm	CFT	UK																		
farm	ANCA	NL																		
LCA	Cap2ER	FR																		
LCA	\$ Mean/IN-out	FR																		
LCA	\$ DECIDE tool	IRE																		
region	Orchidee	FR																		

* field data only
\$ uncertainty/sensitivity analyses before model simulation

Figure 23Figure 15. Overview of the application of the different models and tools in ClieNFarms

3.4.4. Preliminary Model comparisons

At this stage of the project model comparisons is not completed yet (see DL2.4). The intention of the model comparisons is not to rank the models but indicate differences and analyse, and the reasons for these differences in terms of model processes (Tier 1 to 3) data inputs. Each tool and model have a specific purpose and is developed for a specific objective. The suitability of the tools and models depends on the aim of each task.

A comparison of CAP2ER and the Cool Farm Tool (Figure 24) shows that the tools are quite similar in their final result but divert in the amount of CO2 that is emitted for this specific farm. While the approaches in both tools are similar, the CAP2’ER tool is developed on a French data base, while the Cool Farm Tool was developed on global data sets (partly including regional data). However, the differences are not due to the origin of the source data, but in the consideration of GHG emissions for the different parts of the emission process.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

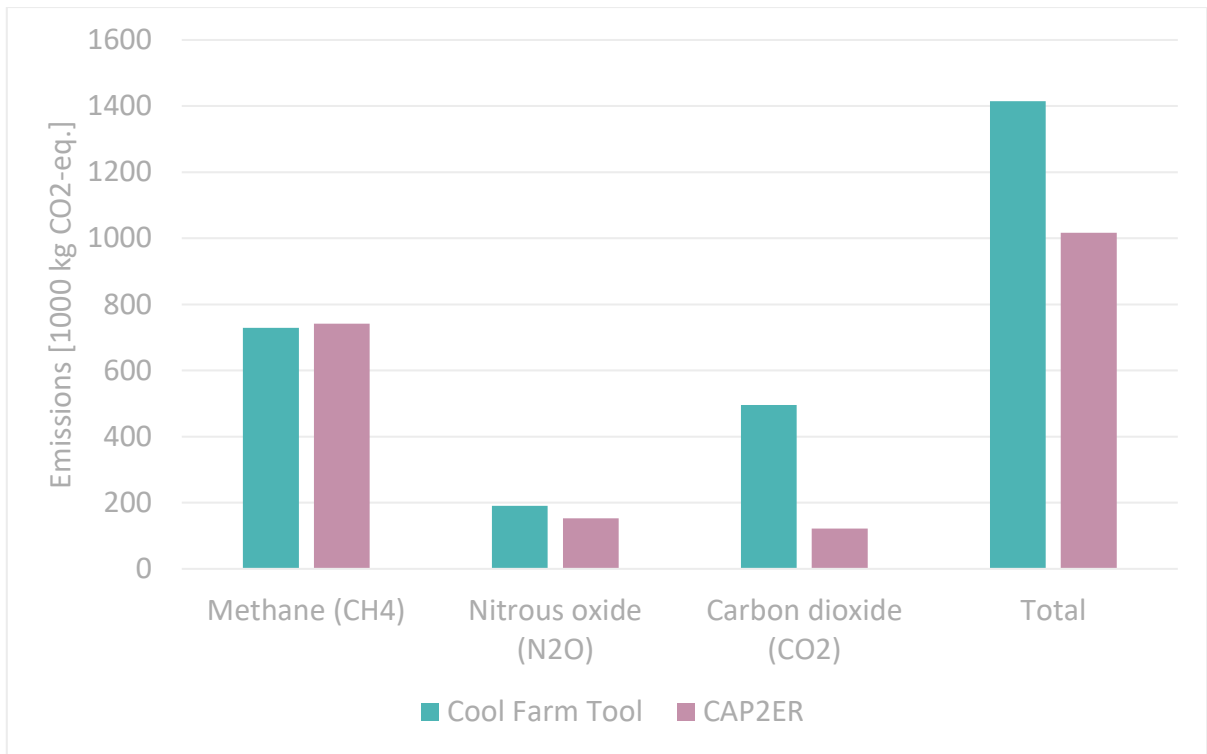


Figure 24: Comparison for a dairy farm using the two GHG emission tools Cool Farm Tool and CAP2ER.

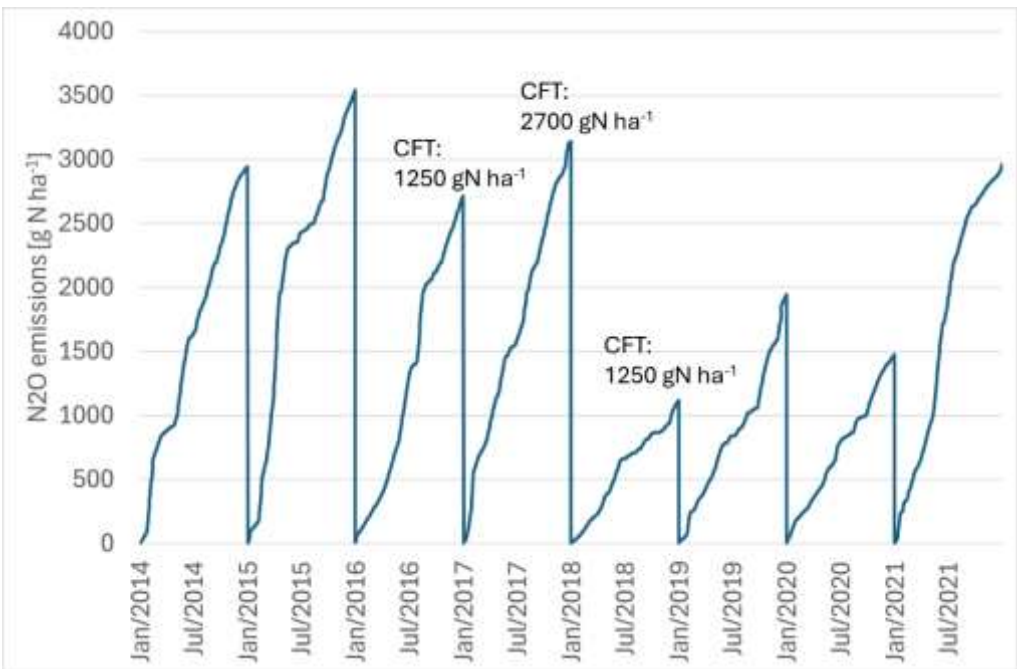


Figure 25: N₂O fluxes of a demonstration farm simulated with DAYCENT. The numbers added in the graph show the corresponding values from the Cool Farm Tool (CFT). For all peaks without a number the CFT simulated no N₂O emissions from the field.

Figure 25 shows the continuous N₂O emissions simulated by DAYCENT, with the corresponding values of the Cool Farm Tool added as numbers in the graph. For most years the Cool Farm Tool did not simulate any N₂O emissions from the field, as there was no mineral or organic fertilizer added during these years.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

However, there were catch crops added in the crop rotation that added nitrogen to the soil. While continuous simulations are able to consider these impacts, farm models that use simple Tier 1 or 2 approaches for annual simulations do not pick up on these impacts. This is similar to impacts on soil organic carbon and temporal variability of variables over time. This is relevant for comparison with measurements, which might not be taken at a moment of average but extreme values or to consider weather impacts to get an actual assessment of the emissions.

3.5. Quality of the results

This section will provide a qualitative analysis of the results and experience applying the models on the I3Ss in ClieNFarms. A quantitative quality check will be part of deliverable D2.4. As mentioned, as ranking of models is not the aim, as first, the correct data for emissions are unknown, second, the results are affected by model applications by different users, which affects the result and, third, a ranking of models and tools is not useful as they are all useful for specific objectives. Therefore, there will be no ranking but a description of similarities and differences between the models and tools.

3.5.1. Challenges in Data collection

The wide range of models affected a large data demand (full data sheet: 93 and light data sheet: 63) due to the varying data requirement for the different models and tools (Figure 4).

- This made the data collection challenging as it was very demanding for the I3S managers, depending on the initial organisation of their farm data and habitude to fill these type of data.
- Even though the list of models was provided and the objective of the tasks explained, there was a demand for clearer details about the returned information. However, even though there were challenges and some additional workload for I3S managers, this task was completed very well.
- Ongoing communication between the WP2, modeller group and the I3S manager group improved further the data, as some data got clearer by added meta-information. There were also questions about the interpretation of the required data in the list (e.g. what calves are listed in the data list).
- Due to the size and structure of the farms, for several I3S field specific data couldn't be provided for all fields, but either data for selected fields or aggregated data were provided.

For testing the impact of gap filling and data interpretation, in a first step the use of the data were left to the modellers. Ongoing tasks will add a second step and define the use and gap filling routines for the use of the data and focus on the differences between models.

3.5.2. Parameterisation and use of the different models and tools

The Cool Farm Tool was used as a standard tool. This meant that all farms will be simulated by the same model/tool. This provides a standard data set, which can be used for comparisons with results of other models. **The Cool Farm Tool was also chosen, as it is developed for its global application and includes almost all crop and livestock options that are required.**

- However, the application of the tool also showed, that for some represented crop or livestock options the tool requires improvements (olives and pigs).

The data collection was organised based on the data demand of all the models in the project (see sections above). This list was aggregated and sent to the I3S managers.

- The main problem for this approach was that I3S managers or advisors had to fill in the list for a couple of farms, needed to search for some specific data or struggled to provide data more specific than the farm scale. The used approach was chosen to understand the data availability and estimate errors for using less or aggregated data.
- In a real-world application tools and models should be picked or adapted to the data availability or additional measurements are required. Impacts of these two options will be discussed below.
- In the project a great data set was provided to the modellers, but as the data was sourced by different people, there were some inconsistency in the data sets and in the way how to fill the

model parameters. Efforts were made to rectify but some of these inconsistencies. While all models were able to run simulations, but there was inconsistency in gap filling (see section 3.5.1).

3.5.3. Critical Analysis of model simulations

The objective of this section is to provide a qualitative analysis of the results to explain and support the advice that is concluded in this deliverable. A quantitative analysis will be part of deliverable D2.4 later in the project.

Complexities of simulated processes in a three-step Tier approach . GHG emission tools use mainly simple factors (Tier 1 and Tier 2) to estimate emissions and carbon sequestration.

- Especially for the latter, this simplification can be very uncertain. In the tools carbon gain or loss is often linked to a management action. The result represents the generic assumption that is added as a factor in the tool. This structure is quite strict and will represent the parameters set in the tool or model.
- This is static in the assessment and for monitoring purposes dynamic changes and local factors are completely ignored. This is especially critical for SOC monitoring and these tools (at least in the actual form and with the actual parameter set) are not suitable for SOC monitoring.
- Likewise crucial parameters and variables like soil properties, environmental conditions (e.g. soil water content and soil temperature) or initial SOC are ignored by these approaches. Therefore, these tools are useful to provide basic assumptions about an expected trend e.g. for decision support, but they must not be used for actual quantification of SOC sequestration.
- **The complexity and interaction of the processes** that are relevant for decisions on the farm scale is not captured by any model or tool (this means tools or models that provide total emissions for the entire farm, not models that focus on individual processes) based on Tier 1 and 2.
- Even though the wide range of activities are considered by some models, these generalising tools use simple empirical correlations to describe impacts and conclude for the emissions. The quality of these results is **sufficient for a support tool, but critical as basis for economic or political decisions**.
- Using more detailed model, e.g. process-based models, could potentially improve results.
- However, these models require more and specific data. Some of these data (e.g. soil characteristics) are often not as standard data available for farms. Even though, the uncertainty of the results can be reduced, the risk for errors is increasing due to the quality and availability of required data.
- Additionally, there is a lack of farm specific process-based models, but the different processes on the farm require the use of several models (cropland specific and livestock specific models, with grasslands covered by cropland modelling).

The experience in ClieNFarms shows, that the collection of the data for the process-based models was difficult and for non-experimental farms impossible without additional measurements.

- National or European measurement campaigns with standard methods that will provide farm-specific data for SOC, bulk density, additional soil parameters would help to improve the applicability of process-based models.
- As an improvement to actual available data sets, location specific (including date) measurements, using a standardised protocol would provide a more standardised data set.

3.5.3.1. Cropland simulations

Data received to simulate processes in a three-step Tier approach .

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

- The data basis provided by the I3S managers for demonstration farms was sufficient to run Tier 3 models (climate data came partly from different sources) for several farms, but these farms were often associated with **research institutions** or part of other projects, which oblige them to have dense and organised data recording, enabling them to provide the required additional data beyond information that is usually available on a standard farm.
- On standard commercial farms (here LCF) Tier 3 models can only be applied with additional measurements on a farm or by using assumptions **that might increase the error** of the simulation.
- In contrast, **the assessment tools** were able to run simulations for all farms that provided data, but the quality of the provided data was diverse.

Considering the different variables that are considered as part of the GHGE balance, the recommendation for using modelling is based on the target emission or purpose of quantifying the emissions. For carbon fluxes Tier 3 model must be used, especially, if the target is SOC change.

- Even though these simulations also show problems (e.g. data availability as mentioned in the paragraph before) and include errors, simpler approaches are no alternative due to the accuracy of the results.
- Beside the “classic” carbon modelling, in ClieNFarms also an integrated option using different methods in combination, to compensate for limitations and allow to get the input parameters required for modelling (see section 3.4.1.3).
 - *CO₂ fluxes can be measured by changes of SOC and biomass, which reflects the carbon balance. While biomass is a short-term storage (at least for plants on farmlands), SOC (also affected by the plant biomass) indicates the long-term balance for carbon fluxes.*
- All model approaches showed to some extent problems, uncertainty and errors for estimating or simulating SOC or SOC changes on the field or farm scale.
- **Therefore, it is not advised to use only modelling to quantify SOC or CO₂ fluxes.**
- Modelling can support direct measurements from the field by interpolating or extrapolating data. However, already for extrapolating data the results depends on the quality of data available to secure high accuracy of the results.
- Beside the already mentioned lack of data or data of sufficient quality, SOC modelling requires information about the chemical stability of the SOC compounds, which can be represented by pools with varying turnover rates and accurate SOC and bulk density values, measured in a appropriate spatial resolution.
- Additionally, most models require a condition specific calibration which is still difficult due to a limited availability of long-term experimental site or long-term monitoring on commercial farms. Models and tools can still be used, but the listed limitations affect the uncertainty and quality of the results.

3.5.3.1. Livestock simulation

For the livestock simulations in ClieNFarms an established French and a Dutch tool was part of the exercise beside tools that are not developed for a specific region. The analysis is ongoing, but overall, the data show comparable results. However, the analysis of CAP'2ER and the Cool Farm Tool showed some differences in the carbon emissions (Figure 24). These differences match the amount of the emission footprint of the imported fertilizer. As CAP'2ER also considers upstream emission footprints, this cannot explain the differences. It seems like based on differences of how specific contributions are considered in the simulation. The analysis is ongoing.

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

- Most critical part of the livestock simulations is the feed and the manure/slurry storage. The feed has an impact about the methane emissions and the storage options can have high contributions to the overall footprint.
- Here the data provided by the different farms divert, which can have crucial impacts of the results using different gap filling options or interpret the provided information. An ongoing analysis will indicate the impacts of these effects on the model results.

In ClieNFarms no Tier 3 model was part of the modelling exercise. Therefore, it is difficult to estimate the different data demand comparability with simpler approaches or the complexity to use these models.

3.5.3.1. *Results on farm scale*

The focus in ClieNFarms is the farm scale. This means all emissions on the farm until farm gate are included in the simulation. Not all models can cover all emission sources.

- Tier 3 models are specialised on individual parts of the farm (e.g. field emissions), while tools and models that cover the entire farm have lower Tier levels.
- Here the main differences between the tools are the consideration of upstream emissions (e.g. for imported mineral fertilizer). A detailed analysis about this and how the results are affected by these differences is ongoing.

The farm tools provide results of the simulated emissions for different sources, which allows the analysis of the most contributing process (Figure 8 and 19).

- Based on this information decisions to reduce emissions can be developed to achieve climate neutral farming.
- For an optimum coverage, different models and tool scan be combined to improve the simulation results for the farm. Each tool and model have advantages and disadvantages and a good combination would provide the best results.
- This would require some knowledge of using the tools and models and the data to run all of them. However, this would allow more detailed simulations for parts on the farm that provide the required data and to consider management options that might be not possible to simulate by each tool or model.

3.5.3.1. *Mediterranean farms*

Mediterranean farms are partly special as the actual crop selection is different (e.g. olives, tomatoes) and as the climate conditions are different which might affect processes and management options.

While in the model results there are no differences in the results for the Spanish or Italian I3S, there were some challenges and problems with the I3S in Portugal. As the I3S is producing olives, hardly any tool or model was able to simulate this and the data basis to derive parameters for models and tools is limited.

- Nevertheless, the Cool Farm Tool offers the option to calculate emissions for olives under the category tree crops. However, this option provides values for emissions of the farm, but does not (or only to a limited amount) include soil carbon sequestration by leaving residues from pruning in the field and do not include the biomass changes by the trees. This has to be complemented by other sources (e.g. regional averages, other models/tools) or the entire simulation has to be done by another model or tool.

- The models RothC, DAYCENT and ECOSSE can simulate GHG emissions and carbon sequestration, but require more specific data, especially for soil properties. There is a model that is specialised on perennial crops (Perennial-GHG), which includes tree crops (Ledo et al., 2018). However, the considered tree crops include only apple, citrus, cacao, coffee, tea and poplar. The work in ClieNFarms on resolving this issue is ongoing.
- Based on the experiences in ClieNFarms it is suggested to use olive tree specialised models and tools or to use process-based biogeochemical models (e.g. RothC, DAYCENT and ECOSSE), which provide options to add the biomass as input parameter (RothC and ECOSSE) or they are already applied on olive orchards and the parameter sets are provided (DAYCENT, Brilli et al., 2019).

3.6. Applicability of the models and tools

This section describes the application of models for different purposes, even so all have the objective of climate neutral farming. The previous sections indicated already the differences in the use and analysis of models and model results for different objectives. Here, the different objectives and interest in the progress towards climate neutral farming is analysed in the context of the use and application of models and tools.

3.6.1. Stakeholder groups and their objectives

There are different ways to use tools and models to monitor impacts, develop strategies or simply support changes towards climate neutral farming. There are three main stakeholder groups involved:

1. farmers or advisors,
2. policymakers,
3. businesses.

The potential application and required accuracy differ for the diverse objectives the different stakeholder groups will use tools and models.

For the different purposes, models and tools can be used to assess the carbon footprint or for monitoring changes in the GHGE balance. In most cases the models and tools can do both, but the quality of the results differs. It should be noted that some tool or models require a licence (e.g. the Cool Farm Tool). The licence might include fees (depending on the stakeholder group using the model or tool). The commercial maintenance of models and tool has the advantage of an continuous updating of the tools and often provided support services. However, depending on the payment structure the use of tools and models might restrict the use depending on the stakeholders.

3.6.1.1. Farmers

For farmer the farm or field scale is the target scale. The results must have high accuracy if they build the basis for subsidies or carbon certificate trading.

- Modelling alone cannot provide the accuracy for these calculations, but it could be one part of a greater integrated approach.
- Here, carbon fluxes should be simulated by Tier 3 models/tools, while N₂O fluxes can be simulated with lower Tier levels.

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- Using model or tool results for decision support or to discover general trends, less accuracy is acceptable as long as the general trend is correctly indicated. Therefore, farm tools on the Tier 1 and Tier 2 basis would be sufficient.

Applied tools (depending on the tool) might be applied by the farmer or the advisors (after some training). The tools provide information about hotspot for GHG emissions among the different activities on the farm and allow to test simple modification and their impacts on the GHG emission balance.

Using simulations as basis for subsidies or to certify carbon gains, the use of farm tools is not accurate enough.

- Here direct soil/farm measurements are necessary. In case models are used to support measurements, only Tier 3 models must be used for accurate simulations.
- These models require model expertise and cannot be used by unexperienced modellers.
- Depending on the changed management action, the use of the models will also require extra measurements to get the input data for running the model.
- Running these models by using low quality data (e.g. default data) will reduce the quality of the simulation results.

3.6.1.1. Policymakers

For policymakers the objectives include the development of guidelines, developing long term strategies for regions or countries, assess actual emissions or monitor changes due to management changes.

- Similar to the section for farmers, tools and simple models can be used to estimate generic trends.
- The Tier 1 and 2 approaches are also sufficient for large scale estimates e.g. on the national scale. These results will contain some uncertainty, but errors will level out and if the number of farm considered is large enough, the estimated average will be relative robust.
- For simulations on **the farm or field scale more accurate models** must be applied, especially if the objective is the assessment or monitoring for the payment of subsidies. As mentioned, there are limitations about the use of models for monitoring GHG emission changes on the field or farm scale.
- **For the accuracy, Tier 3 models are required**, but these models require more and accurate data. Additionally, the application of these models requires expertise in modelling. This means most likely the involvement of a consultancy or an expert team to do the simulations.

In future, there will be solutions for applying more complex models, as for example in the COMET Farm Tool which has an interface to reduce the complexity of the usage of a process-based model. Additional, post-processing routines can be integrated to simplify the data analysis.

In some cases there seems to be a miss-understanding that Tier 3 models are better in general. So, there is a shift for national SOC inventories towards Tier 3 level models. Even though this reduces the uncertainty, as more accurate simulations are applied, but it increases the risk for error.

- These errors are usually introduced by the input data, in form of aggregation error, gap filling error, interpolation error, extrapolation error, etc. In most countries the data basis to run Tier 3 models is not good enough.
- Additionally, the data quality is also not always up to the required level. It should also be noted that the data quality might vary between the countries, which would affect the simulation results in different ways. Most important for all further developments is the establishment of unified spatial data of high and transparent standards.

3.6.1.1. Business applications

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The group of businesses includes also several interest groups. The focus in ClieNFarms is on two groups: carbon certificate trading businesses and food companies. While the carbon trading companies focus more on monitoring changes, the food sector requires an production line assessment of the carbon footprint.

3.6.1.3.1. *Carbon certificate trading*

For carbon trading accuracy of the emissions is most important especially for the changes.

- Simulating changes is often easier, as biases or assumptions applied on both (first and second) measurements will affect the results in a comparable amount and the error is potentially lower for the difference or change than on the absolute value.
- However, uncertainties and estimated errors will affect a reduction of the price paid for the carbon certificate that is generated by the farmer. Therefore, the models and tools should be chosen accordingly.

3.6.1.3.2. *Food sector*

For the food sector the precision of the GHGE assessments is important. Each product will be linked with a carbon footprint and the entire production line will be included to this footprint. As the products does not come from one but several farms, more generic approaches as e.g. provided by the farm tools are sufficient to estimate the GHGE.

- However, a robust and transparent simulation of the GHGE footprint is important, but some error and uncertainty can be accepted, as this will be not the basis of trading or will affect any direct economic value, but the information must be robust and transparent as information to the customer.
- Farm specific assessment tools are often sufficient, as no single farm results are used for the footprint, but a large number of farms. Individual farm errors level out on this large scale.
- It should be noted, that here generic tools might be beneficial, as farms might be located in different regions. Local tools could also be used, but might affect the results, if they are not directly comparable.

3.6.2. **Using models to assess greenhouse gas emissions**

For GHGE assessment precision is most important to have a correct value for the actual emissions. Assessments are usually used for farms, supply chains or national inventories.

For all these objectives the accuracy has not the highest priority and a certain level of uncertainty can be accepted. This is particularly true when the data is up-scaled (e.g. supply chains estimate GHGE for different farms and other factors, inventories make large scale assumptions) detailed simulations are not necessary or possible but simpler approaches like Tier 1 and Tier 2 approaches are most suitable.

Farm tools are the best option to assess N₂O emissions on the farm scale. As mentioned above, the uncertainty of other options are also high and the complexity of measurements make the farm tools a acceptable compromise to provide data for N₂O emissions.

3.6.3. **Using models for monitoring greenhouse gas emission changes**

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

For monitoring changes monitoring/measuring, reporting and verification (MRV) systems allow a structured and robust monitoring of SOC and GHG emissions over longer periods.

- In most case a baseline and action (mean changes of managements to reduce emissions or increase SOC) affected values are quantified to report carbon gains or emission reductions.

Similar to the approach in ClieNFarms, the baseline is usually the initial condition and the action affected variable the final result. Beside other options, models are used in a range of MRV systems to simulate the changes or support the estimation (Black et al., 2022; Oldfield et al., 2021).

- However, crucial aspect in the use of the application of models in MRV systems is not clarified.
- The application of the model has a minor impact on the result rather than the quality of available and used data and the modelling experience of the user of the model.
- The best model cannot perform, if the data availability is insufficient or the user does not have any experience in applying the model.
- Simpler approaches provide in these situations often better or at least comparable results. Similar, models can be applied in any case, but the performance will differ. As there is a lack of values to evaluate the results, the accuracy remains in most cases unclear.
- Data availability and quality is key for good simulation results.

The diversity of models, data demand and impacts of data on the results is already presented and discussed in the previous sections. As MRV systems can be used on different scales, the data availability and quality will vary accordingly. Here, the focus will be on a regional (sub-national) and field/farm scale application.

4 Conclusions

The application of models requires data. The strong emphasis on data and data collection in this deliverable about modelling should highlight that the quality of the results and the ability of using modelling is strongly linked to data availability and data quality.

- The data collection in ClieNFarms showed that with clear communication and explanation, is a wide range of farm data became accessible.
- These data were usually not provided by farmers to advisors or researchers.
- If the protocol and the objective of the data collection is clear and transparent, data for farm models should be accessible from most farms in Europe. Advices and protocols for the data collection should be provided.

The data availability was restricted to Tier 1 and Tier 2 model. Tier 3 models cannot be run with generic farm data, but require additional measurements.

- While in ClieNFarms only data for two years were collected, a continuous data collection for several years would be beneficial to monitor annual variations and capture impacts of crop rotation.
- If the data collection is restricted to a standard data set that would allow the use of one or several models/tools, over time the data collection will improve and gaps would be avoidable.
- However, if gap filling is required, this should be standardised.

There is no best tool or model to use for simulating or monitoring GHG emissions, but a set of options for different purposes. The deliverable outlined a wide range of different tools and models for a variety of applications.

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- For the targeted purposes the accuracy that a tool/model can achieve is not the only criteria that is relevant to choose the most suitable option for a specific problem.
- Data demand, kind and resolution of required and available data, consideration of offsets and additional target variables are additional criteria, among others.

The tools and models used in ClieNFarms are developed for different objectives and show a range of advantages and disadvantages to support climate neutral farming.

- The quality of the results depends on the context of application. While the results as a support system are sufficient, the application of the tools and models on the field and farm scale shows too high uncertainty and potential inaccuracy.
- On the field or farm level the tools and models are not good enough to estimate changes for economic (e.g. subsidies, carbon certificate trading) decisions.
- Error and uncertainty associated with the results are too high to make field or farm specific decisions.
- Also Tier 3 models will show some error due to heterogeneity of required input data, data aggregation effects, model errors and other problems.
- Even, if the missing data will be measured to run a model, the result on its own is not good enough to quantify GHG emission balance on the field or farm scale. However, the results can still be used for assessments or for monitoring, as long as they are complementing measurements of the target variables on the field or farm.

Non CO₂ emissions. In contrast to CO₂ fluxes and SOC changes, the N₂O and CH₄ fluxes are smaller and the annual balance is dominated by peaks, which makes also the measurements very complex and uncertain. The small fluxes and the high global warming potential translate small errors on the individual fluxes into large errors in the overall GHGE balance. Measurements are similar affected like the modelling.

- For N₂O and CH₄ all quantification methods exhibit high uncertainty and the field measurements are complex. For this case, modelling can be a good alternative to quantify the fluxes. The quality gap for results between measurements in the field (spatial representation of the fluxes) and modelling is considerable smaller for the non-CO₂ fluxes and modelling can provide comparable results.
- In barns, measurements over the herd might be more accurate than empirical model approaches and less complex than field measurements.

Regional or national tools and models . Several tools in ClieNFarms are developed on regional or national data sets. By chance, in ClieNFarms, these tools are mainly focussing on dairy farms.

- Potentially, tools and models with a national or regional focus have the potential to provide better, more accurate results.
- However, this depends on the data basis that is used to develop these tools (if the data basis is too small, the tools will be most likely worse than generic tools).
- Additionally, it depends on generic tools might be affected by data aggregation including data from other regions to use different values than the more local tools.

Generic models and tools. As an example, the generic Cool Farm Tools uses, based on data availability, for some variables local factors (e.g. feed information).

Means InOut is the another generic tool, whereas ANCA and CAP'2ER are national (Dutch and French, respectively) tools. When utilising regional or national tools, it's crucial to ensure that the underlying dataset is robust enough, incorporating a large volume of data that adequately represents regional or national conditions and that the results are comparable with other tools.

The comparability is part of the ClieNFarms exercise and first results do not show concerns, but the exercise is not yet completed.

Remote sensing and modelling. Beside the farm tools and crop models, there are two model approaches used in ClieNFarms that use remote sensing data for their modelling. ORCHIDEE is one of these models and the only option in the project to model albedo. The method is optimised in ClieNFarms and will provide robust estimates for albedo, also for spatial simulations. The second model is SAFYE-CO2+AMG which uses remote sensing to estimate the biomass input to the soil.

These approaches provide potential for spatial simulations of SOC, but may not necessarily offer significant advantages on the field or farm scale.

Field vs. farm scale models. The main analysis of modelling focusses on the field and farm scale. Using models for large scale simulations on the regional or national scale. Most of the models in ClieNFarms are not designed for large scale simulations. DAYCENT is a model that is used for the US GHG emission inventories.

- However, for large scale simulations, spatial data are crucial and the quality of the spatial simulations depend on the quality of the available input data.
- On the large-scale, Tier 1 and Tier 2 approaches yield comparable results to Tier 3 approaches, but a higher uncertainty.

As mentioned in the previous paragraph the SAFYE-CO2+AMG combination will provide the option to large scale SOC simulations using biomass measurements from remote sensing observations.

What use for stakeholders. The stakeholder specific use of the tools and models is related to the target scale, most relevant unit and the usability.

The scale defined for various tools and models. Focussing solely on one method to express the emissions (e.g. total emissions per farm, emissions per area or emissions per product) diminishes the information and may bias the the decision-making.

Even though, actions may achieve changes in the target unit, disregarding the other units, could negate benefits, due to unintended side effects, potentially resulting in an overall negative environmental impact. The usability of tools and models for the different stakeholders is difficult to conclude.

- In the actual form most tools or models have to be used by modellers.
- Cool Farm Tool for instance, is designed for non-modellers and provides an infrastructure to train people to use the tool. This would enable farm advisors or policy makers to use the tool.
- Other farm tools show similar potential, but do not yet have the infrastructure and would require some work to simplify the use of these tool.

Overall, all models and tools can be updated to a non-modeller usability state, as soon as they are selected or considered to be relevant.

- The additional work would require to develop an interface.
- Beside the usability, long-term maintenances is a crucial factor. Tools and models are regularly updated. This is necessary to update parameters, resolve bugs, add relevant processes or new knowledge and adapt to new developments of measurement techniques and data availability.

Except the Cool Farm Tool, for most tools and models the maintenance is funded by research projects, which is a non-sustainable structure. Here the EU could think about either encouraging privatisation of tool and models (disadvantage would be costs for users) or provide/support teams/funding for a sustainable funding of the developer teams.

MRV systems for SOC modelling.

In MRV systems for SOC, **modelling** can only play a supportive role, as the data demand, errors and uncertainty affects the accuracy.

- However, it can be used to support field measurements by e.g. temporal interpolation of field measurements, sampling stratification (less likely, as this would require a high data demand with high spatial resolution) or as part of the verification process.

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- Farm tools or other Tier 1 and Tier 2 approaches are not good enough to quantify SOC or CO₂ emissions on the field or farm scale, but can support this by estimating the offsets due to N₂O or methane emissions.
- For regional or national scales, Tier 1 and Tier 2 based tools will be more suitable, as the data availability and quality will affect Tier 3 based model approaches, which will be represented in an increased error. The larger the scale the more likely the error of the Tier 3 model approaches will match the uncertainty of the Tier 1 and Tier 2 tools.

The main objective of MRV systems is to monitor changes of SOC over time.

- Tier 1 and Tier 2 farm tools are in most cases developed for farm assessments and indicating trends for management changes, but not for accurate predictions of changes in emissions.
- The use in MRV systems will only show generic impacts of management changes, which will be almost similar to action-based payments, rather than impact-based solutions.
- Due to the diversity of impacts on the larger scale, extremes will be compensated which will result in a sufficient quality of the results on the larger scale (the number of considered farms has to represent the heterogeneity of the different farms).

Summary,

- *models and tools are useful options for predicting trends and providing averages on larger scales, but lacking accuracy for location specific quantitative results.*
- *The quality of location specific quantitative simulation can be improved by a high-quality data set.*
- *It is most suitable to use models and tools complementary to direct measurements (of the target variables) and other approaches.*

If MRV systems using accurate measurements, models can be used for the verification of results. In several cases modelling can be used to estimate potential emission off-sets by N₂O or CH₄ emissions.

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Annex Model introduction/SWOT framework tables

- **SAFYE-CO2**

GENERAL INTRODUCTION	Tool/model name	SAFYE-CO2
	Description	SAFYE-CO2 crop model has been developed at CESBIO since 2012. It assimilates high resolution remote sensing data and allows to simulate biomass, yields, CO₂ and water (ETR) fluxes. Recently it has been coupled to the AMG model which allows to estimate C-budgets of crops at plot resolution. See https://www.cesbio.cnrs.fr/agricarboneo/saye-co2/
	Scope of application (whole farm/field / soil C/soil GHG/	Field at landscape scale
	Sector (agri-food/dairy/crop/orchard/etc)	crop
	What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/ Monitoring progress/ Certification/ Comparison)	Benchmarking/ Monitoring progress/ Certification/ Comparison
	Indicators (GHG/biodiversity/socioeconomic/other)	Carbon and water budget components, biomass, yield
	Geographic scope (global/ which region?)	Regional: France
	Type of modelling	
	• Quantitative • Semi-quantitative • Qualitative	X

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	If quantitative modelling is used, • Empirical models	
	• Dynamic process-based models	X
	• TIER level?	3
	Whether ISO 14040/44 compliance? (yes/no)	no
	Whether Uncertainty reported? (yes/no)	no
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++)	+++
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++)	+++
USER FRIENDLINESS	Is the tool readily available? (online or ready to download/ requires installation/ requires permission /password/ Not available)	requires permission
	Is support available? (e.g., contact number)	Yes: ahmad.albitar@gmx.com
	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file.	Yes but upon request, contact ahmad.albitar@gmx.com
	Target User (Any/Some knowledge required/Trained user/Expert)	Trained user
RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan)	Shape files, graphics, tabular
	Does the tool provide a breakdown of where emissions occur?	The model simulates the components of the C and water budgets

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

TRANSPARENCY	What is the Upfront level of transparency of emission factor data (Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	No GHG emissions calculated
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/ for few/none)	
	Are Data sources and methods available (Yes/no)	Yes
	Any other strength?	Require few management data, allows high spatial resolution estimates of the C budget components over large areas
	Any other weakness?	Few crop species parametrized (only 4), skills in modelling and remote sensing required, no front end, no GHG emissions estimates, not applicable for prognostic modelling. Requires LAI index dynamic maps as inputs

Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
Land Use	Land use change	No
Machinery-consumption	Diesel Consumed	No
	Farm machinery	No
	Purchased Electricity (on farm)	No
	Transport	No
	Buildings	No
	Final Distribution	No
Emissions from field	N2O emissions mineral Fertiliser	No

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	N2O emissions from residues (ploughed in)	No
	N2O emissions from organic fertilization (direct and indirect)	No
	NH3 emissions from organic fertilization (direct and indirect)	No
	Lime addition CO2	No
	Soil CO2 tillage	No
	Soil CH4 emission/uptake	No
Emission related to Livestock	Emissions from Manure storage	No
	Emissions from animal housing	No
	Emissions from animal	No
Grain quality	C/N ratio in grain	No
	other	
Other	Fertilizer manufacture	No
	Albedo	No
	Ground water level	No
Any other (please add comment)	Heat impacts	Yes

- **Systerre**

GENERAL INTRODUCTION	Tool/model name	Systerre
	Description	Multicriteria assessment tool which uses data from farms to calculate a range of indicators at farm or plot scale.
	Scope of application (whole farm/field / soil C/soil GHG/	Whole farm & field
	Sector (agri-food/dairy/crop/orchard/etc)	Crop
	What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/	Assessment / Comparison

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	Monitoring progress/ Certification/ Comparison)	
	Indicators (GHG/biodiversity/socioeconomic/ other)	GHG + socioeconomic
	Geographic scope (global/ which region?)	Global
	Type of modelling	
	• Quantitative	Quantitative
	• Semi-quantitative	
	• Qualitative	
	If quantitative modelling is used, • Empirical models	Calculations
	• Dynamic process-based models	
	• TIER level?	GIEC 2006b (tier 1) EMEP/EAA 2009 & Ecoinvent Agribalyse (tier 1 & tier 2)
	Whether ISO 14040/44 compliance? (yes/no)	No
	Whether Uncertainty reported? (yes/no)	No
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++)	++
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++)	+++
USER FRIENDLINESS	Is the tool readily available? (online or ready to download/ requires installation/ requires permission /password/ Not available)	Requires an account
	Is support available? (e.g., contact number)	Yes
	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file.	Yes https://www.systerre.fr/systerre/home/documentation/notice
	Target User (Any/Some knowledge required/Trained user/Expert)	Some knowledge required

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RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan)	Tabular
	Does the tool provide a breakdown of where emissions occur?	No
TRANSPARENCY	What is the Upfront level of transparency of emission factor data (Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	The coefficients used for primary energy consumption and greenhouse gas emissions originate principally from the GES'TIM v1.2 methodological guide, with recalculation according to the GWP of the IPCC 2007 (rather than the GWP of the IPCC 2001, as used in GES'TIM).
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/ for few/none)	For all
	Are Data sources and methods available (Yes/no)	Yes
	Any other strength?	Gives economical analysis of the farm
	Any other weakness?	Doesn't assess soil carbon

Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
Land Use	Land use change	
Machinery-consumption	Diesel Consumed	X
	Farm machinery	X
	Purchased Electricity (on farm)	
	Transport	
	Buildings	
	Final Distribution	

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

Emissions from field	N2O emissions mineral Fertiliser	X
	N2O emissions from residues (ploughed in)	
	N2O emissions from organic fertilization (direct and indirect)	X
	NH3 emissions from organic fertilization (direct and indirect)	X
	Lime addition CO2	
	Soil CO2 tillage	
	Soil CH4 emission/uptake	
Emission related to Livestock	Emissions from Manure storage	CO2
		N2O
		CH4
	Emissions from animal housing	CO2
		N2O
		CH4
	Emissions from animal	CO2
		N2O
		CH4
Grain quality	C/N ratio in grain	
	other	
Other	Fertilizer manufacture	
	Albedo	
	Ground water level	
Any other (please add comment)	Heat impacts	

- **CAP'2ER**

GENERAL INTRODUCTION	Tool/model name	CAP'2ER
	Description	CAP'2ER were developed by IDELE in a multi-stakeholder partnership to build a common understanding about what the environmental footprint of crop and livestock is, and how to improve the environmental performance of production systems.
	Scope of application (whole farm/field / soil C/soil GHG/	Whole farm
	Sector (agri-food/dairy/crop/orchard/etc)	Dairy Cattle Beef Cattle Dairy Sheep Meat Sheep Goats Annual crops Poultry (in development) Pig (in development)
	What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/ Monitoring progress/ Certification/ Comparison)	Assessment / Market access / Comparison/monitoring progress/carbon gain certification -CARBON AGRI
	Indicators (GHG/biodiversity/socioeconomic/other)	GHG emissions / Air quality / Water quality / Fossil Energy consumption / Irrigation / Pesticides use / Soil conservation / Renewable Energy production / Soil Carbon storage / Biodiversity / People food/farm economic data/working condition
	Geographic scope (global/ which region?)	France and any other countries with specific parameters
	Type of modelling	
	• Quantitative	X
	• Semi-quantitative	
	• Qualitative	

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	If quantitative modelling is used, • Empirical models	yes
	• Dynamic process-based models	Yes
	• TIER level?	Tiers 1 2 and Tier 3
	Whether ISO 14040/44 compliance? (yes/no)	Yes
	Whether Uncertainty reported? (yes/no)	no
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++)	+ Level 1: 1 h30 Level 2: 0,5 to 1 day
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++)	+++ Formal obligatory training
USER FRIENDLINESS	Is the tool readily available? (online or ready to download/ requires installation/ requires permission /password/ Not available)	Online, need an account
	Is support available? (e.g., contact number)	Yes, ticket online system
	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file.	Yes in French and English in a simplified version. The whole methodology will be translated in English for June 2023.
	Target User (Any/Some knowledge required/Trained user/Expert)	Trained user
RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan)	Tabular / Graphical / Actions to plan
	Does the tool provide a breakdown of where emissions occur?	Yes
TRANSPARENCY	What is the Upfront level of transparency of emission factor data	Full & detailed disclosure of data

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	(Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/ for few/none)	For all
	Are Data sources and methods available (Yes/no)	Yes
	Any other strength?	A benchmarking per system of production to identified improvement sources for every environmental result and technical results. Export/import of data and API. Tools link to the methodology CARBON AGRI => carbon reduction certification in France
	Any other weakness?	

Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
Land Use	Land use change	Yes
Machinery-consumption	Diesel Consumed	Yes
	Farm machinery	No
	Purchased Electricity (on farm)	Yes
	Transport	No
	Buildings	No
	Final Distribution	No
Emissions from field	N2O emissions mineral Fertiliser	Yes
	N2O emissions from residues (ploughed in)	Yes
	N2O emissions from organic fertilization (direct and indirect)	Yes
	NH3 emissions from organic fertilization (direct and indirect)	Yes
	Lime addition CO2	No

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	Soil CO2 tillage	No
	Soil CH4 emission/uptake	No
Emission related to Livestock	Emissions from Manure storage	CO2 : No
		N2O : Yes
		CH4 : Yes
	Emissions from animal housing	CO2 : No
		N2O : Yes
		CH4 : Yes
	Emissions from animal	CO2 : No
		N2O : Yes
		CH4 : Yes
Grain quality	C/N ratio in grain	No
	other	
Other	Fertilizer manufacture	Yes
	Albedo	No
	Ground water level	No
Any other (please add comment)	Heat impacts	No

- **DECiDE**

GENERAL INTRODUCTION	Tool/model name	DECiDE
	Description	DECiDE is a tool based on the Life Cycle Assessment (LCA) method. It assesses the energy consumption, greenhouse gas emissions and ammonia emissions of Walloon farms at the farm or production unit level. DECiDE also allow identification of the strengths and weaknesses of farms by comparing them with reference farms. In the future, DECiDE will integrate new environmental, but also economic and social indicators in order to look at farms in their entirety. http://decide.cra.wallonie.be/fr
	Scope of application	Whole farm and its components (fields, herds and infrastructures)

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	(whole farm/field / soil C/soil GHG/	
	Sector (agri-food/dairy/crop/orchard/etc)	Crops, dairy and beef cattle farming and mixed farms between these production units. Adaptation of DECiDE for small ruminant (sheep and goat) and monogastric productions (laying hens, broiler chicken and pig production) is on process.
	What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/ Monitoring progress/ Certification/ Comparison)	Development and maintenance of the tool Benchmarking, assessment and reporting
	Indicators (GHG/biodiversity/socioeconomic/other)	Currently, GHG, energy, ammonia and the overall and electricity autonomy of the farm. In the future, new environmental (N balance, pesticides, etc.) and socio-economic indicators
	Geographic scope (global/ which region?)	Walloon region
	Type of modelling	
	• Quantitative	X
	• Semi-quantitative	
	• Qualitative	
	If quantitative modelling is used, • Empirical models	x
	• Dynamic process-based models	
	• TIER level?	Tier 2 and others modellings
	Whether ISO 14040/44 compliance? (yes/no)	Yes
	Whether Uncertainty reported?	No

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	(yes/no)	
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++) 	+
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++) 	+++
USER FRIENDLINESS	Is the tool readily available? (online or ready to download/ requires installation/ requires permission /password/ Not available) 	Online. The tool requires registration with an email address
	Is support available? (e.g., contact number) 	An email address
	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file. 	User's guide and methodological guide available on request or given at training courses.
	Target User (Any/Some knowledge required/Trained user/Expert) 	Agricultural advisors and farmers
RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan) 	Single number, graphical and tabular
	Does the tool provide a breakdown of where emissions occur? 	Yes, graphs and/or tables provide direct and indirect emissions such as the distribution of the main emissions in the farm.
TRANSPARENCY	What is the Upfront level of transparency of emission factor data 	Limited disclosure of data

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

	(Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/for few/none)	For all
	Are Data sources and methods available (Yes/no)	Yes, in the methodological guide
	Any other strength?	The tool is: - Free - Available for several types of production - Uses data specific to Wallonia - Allows comparison with other farms - Possibility of importing part of the data by the accounting - Great flexibility in terms of computing.
	Any other weakness?	The tool is: - At present, not available for other livestock than cattle - Not all agro-ecological techniques are considered yet - Requires training to understand its use

Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
Land Use	Land use change	X
Machinery-consumption	Diesel Consumed	X
	Farm machinery	X
	Purchased Electricity (on farm)	X
	Transport	X
	Buildings	X

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	Final Distribution	
Emissions from field	N2O emissions mineral Fertiliser	X
	N2O emissions from residues (ploughed in)	X
	N2O emissions from organic fertilization (direct and indirect)	X
	NH3 emissions from organic fertilization (direct and indirect)	X
	Lime addition CO2	
	Soil CO2 tillage	X
	Soil CH4 emission/uptake	
Emission related to Livestock	Emissions from Manure storage	CO2 x
		N2O x
		CH4 x
	Emissions from animal housing	CO2 x
		N2O x
		CH4 x
	Emissions from animal	CO2 x
		N2O x
		CH4 x
Grain quality	C/N ratio in grain	
	other	
Other	Fertilizer manufacture	x
	Albedo	
	Ground water level	
Any other (please add comment)	Heat impacts	
All the processes mentioned above	Ammonia – energy utilization	

D2.2 Guidelines for use of models “how to do and what to use”, MRV(-automatization), data harmonization and farm monitoring

- **MEANS platform and MEANS InOut**

GENERAL INTRODUCTION	Tool/model name	MEANS platform and MEANS InOut
	Description	The MEANS platform (MulticritEria Assessment of Sustainability) is an IT platform dedicated to multicriteria evaluation of plant and animal production systems and the processing of agricultural product. It provides tools and databases for calculating sustainability indicators derived from research. It provides free access to a number of sustainability assessment software packages. It has developed its own MEANS-InOut software for performing the inventory phase required for environmental assessments using Life Cycle Assessment (LCA). It provides access to Simapro software to finalize LCA studies. The MEANS platform the platform is co-developed and managed by INRAE, National Research Institute for Agriculture, Food and Environment, and CIRAD, the French agricultural research and cooperation organization working for the sustainable development of tropical and Mediterranean regions.
	Scope of application (whole farm/field / soil C/soil GHG/	Whole farm and its components (fields and herds)
	Sector (agri-food/dairy/crop/orchard/ etc)	Annual and perennial crops, bovine, pig, poultry production
	What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/ Monitoring progress/	Assessment/ Comparison

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	Certification/ Comparison)	
	Indicators (GHG/biodiversity/socioeconomic/other)	A large set of life cycle assessment mid-point impact indicators (e.g. climate change, acidification, eutrophication, fine particulate matter formation, human toxicity, ecotoxicity, land use, water use, energy use, mineral resource scarcity) and endpoint indicators (damage to human health, damage to ecosystems, damage to resource availability).
	Geographic scope (global/ which region?)	Europe
	Type of modelling	
	• Quantitative	X
	• Semi-quantitative	
	• Qualitative	
	If quantitative modelling is used,	X
	• Empirical models	
	• Dynamic process-based models	
	• TIER level?	
	Whether ISO 14040/44 compliance? (yes/no)	Yes
	Whether Uncertainty reported? (yes/no)	Can be done but demands more work.
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++)	+++
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++)	++++
USER FRIENDLINESS	Is the tool readily available?	MEANS-InOut can be made available free of charge for 6 months, without

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	(online or ready to download/ requires installation/ requires permission /password/ Not available)	user support, or with a paid support contract for one year.
	Is support available? (e.g., contact number)	Yes
	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file.	Yes https://www6.inrae.fr/means_eng/Presentation
	Target User (Any/Some knowledge required/Trained user/Expert)	Trained user and expert
RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan)	Tabular and graphical
	Does the tool provide a breakdown of where emissions occur?	Yes
TRANSPARENCY	What is the Upfront level of transparency of emission factor data (Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	Full & detailed disclosure of data
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/ for few/none)	For all
	Are Data sources and methods available (Yes/no)	Yes
	Any other strength?	
	Any other weakness?	

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Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
Land Use	Land use change	X
Machinery-consumption	Diesel Consumed	X
	Farm machinery	X
	Purchased Electricity (on farm)	X
	Transport	X
	Buildings	X
	Final Distribution	X
Emissions from field	N2O emissions mineral Fertiliser	X
	N2O emissions from residues (ploughed in)	X
	N2O emissions from organic fertilization (direct and indirect)	X
	NH3 emissions from organic fertilization (direct and indirect)	X
	Lime addition CO2	X
	Soil CO2 tillage	X
	Soil CH4 emission/uptake	X
Emission related to Livestock	Emissions from Manure storage	CO2 X
		N2O X
		CH4 X
	Emissions from animal housing	CO2 X
		N2O X
		CH4 X
	Emissions from animal	CO2 X
		N2O X
		CH4 X
Grain quality	C/N ratio in grain	
	other	
Other	Fertilizer manufacture	X
	Albedo	

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	Ground water level	
Any other (please add comment)	Heat impacts	

- **ORCHIDEE**

GENERAL INTRODUCTION	
Tool/model name	ORCHIDEE
Description	ORCHIDEE is the land surface model of the IPSL (Institut Pierre Simon Laplace) Earth System Model. Hence, by conception, the ORCHIDEE model can be run coupled to a global circulation model. In a coupled set-up, the atmospheric conditions affect the land surface and the land surface, in turn, affects the atmospheric conditions. Coupled land-atmosphere models thus offer the possibility to quantify both the climate effects of changes in the land surface and the effects of climate change on the land surface. However, when a study focuses on changes in the land surface rather than on the interaction with climate, ORCHIDEE can be run off line as a stand-alone land surface model. The stand-alone configuration receives the atmospheric conditions such as temperature, humidity and wind, to mention a few, from the so-called ‘forcing files’. Unlike the coupled set-up, which needs to run at the global scale (but with the possibility of a regional zoom), the stand alone configuration can cover any area ranging from the global domain to a single grid point.
Scope of application (whole farm/field / soil C/soil GHG/	field level (incl multiple soil, litter and crop compartments, CO ₂ , water, energy fluxes)
Sector (agri-food/dairy/crop/orchard/etc)	crop, grass, forest
What is the Stated purpose? (Knowledge transfer/ Benchmarking/ Assessment/ Reporting/ Market access/ Monitoring progress/ Certification/ Comparison)	
Indicators (GHG/biodiversity/socioeconomic /other)	GHG

Geographic scope (global/ which region?)	site to global	
Type of modelling		
• Quantitative	X	
• Semi-quantitative		
• Qualitative		
If quantitative modelling is used,		
• Empirical models		
• Dynamic process-based models	X	
• TIER level?		
Whether ISO 14040/44 compliance? (yes/no)	no	
Whether Uncertainty reported? (yes/no)	no (default)	
RESOURCE INTENSIVENESS	Time requirement Time necessary to conduct one study <1 day (+) to <1 month (++++)	++++
	Skill requirement to run the tool (indicate level) (No skill + to formal obligatory training +++)	++++
USER FRIENDLINESS	Is the tool readily available? (online or ready to download/ requires installation/ requires permission /password/ Not available)	open source software, but it requires adaptation to the computing infrastructure (for which no support is provided)
	Is support available? (e.g., contact number)	no (default), only via pre-defined collaboration with ORCHIDEE team members

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	Are manuals/guidelines provided? (availability of documentation?) If yes please add the link or attach the file.	yes (but limited): https://forge.ipsl.jussieu.fr/orchidee/wiki/GroupActivities/Training
	Target User (Any/Some knowledge required/Trained user/Expert)	Expert, Scientist
RESULT PRESENTATION/INFORMATIVE	What format are results provided in? (Tabular/graphical/single number/ actions to plan)	
	Does the tool provide a breakdown of where emissions occur?	separates between plant and soil emissions
TRANSPARENCY	What is the Upfront level of transparency of emission factor data (Full & detailed disclosure of data/Limited disclosure of data/not disclosed)	open source / transparent
	Does it explain choices, assumptions, uncertainties? (for all/for all but few/ for few/none)	for few
	Are Data sources and methods available (Yes/no)	yes, open source
	Any other strength?	physical climate impacts, land-climate feedbacks
	Any other weakness?	

Process details (if the following processes are included)? Not sure of we need to ask this. More processes can be added

Group	Processes, estimates, outputs	(yes/no) or tick
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Land Use	Land use change	yes
Machinery-consumption	Diesel Consumed	no
	Farm machinery	no
	Purchased Electricity (on farm)	no
	Transport	no
	Buildings	no
	Final Distribution	no
Emissions from field	N2O emissions mineral Fertiliser	yes (as part of soil N2O emissions)
	N2O emissions from residues (ploughed in)	yes (as part of soil N2O emissions)
	N2O emissions from organic fertilization (direct and indirect)	yes (as part of soil N2O emissions)
	NH3 emissions from organic fertilization (direct and indirect)	yes (as part of soil N2O emissions)
	Lime addition CO2	no
	Soil CO2 tillage	no
	Soil CH4 emission/uptake	no
Emission related to Livestock	Emissions from Manure storage	CO2 no
		N2O no
		CH4 no
	Emissions from animal housing	CO2 no
		N2O no
		CH4 no
	Emissions from animal	CO2 no
		N2O no
		CH4 no
Grain quality	C/N ratio in grain	no
	other	no

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Other	Fertilizer manufacture	no
	Albedo	yes
	Ground water level	no (but soil moisture)
Any other (please add comment)	Heat impacts	soil thermics are computed