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Opportunities and limitations of farm-level greenhouse gas accounting tools: An overview based on experience from practice

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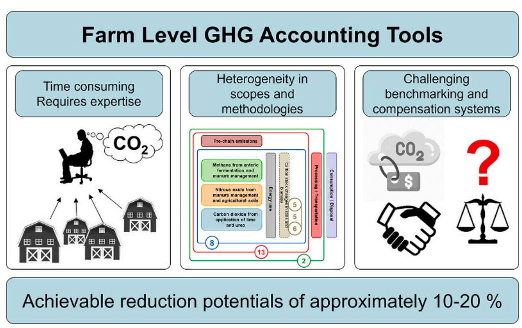
HIGHLIGHTS

- Farm-level greenhouse gas accounting tools are best suited for advisory purposes
- Diversity in scope and methodology hamper comparisons between farm-level tools
- Farm-level emission assessments require sophisticated tools and extensive expertise
- Farm heterogeneity exacerbate fair GHG benchmarking and compensation systems
- Agricultural climate targets can hardly be achieved by farm-level interventions only

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture is a major contributor to greenhouse gas (GHG) emissions. Farm-level GHG accounting tools are used to identify mitigation measures and to monitor, report and verify (MRV) GHG profiles and emission reductions. Here we explore opportunities and limitations of farm-level GHG accounting tools based on a global survey covering the practical application of 23 tools used in 30 projects assessing approximately 40′000 farms, and an extensive literature review. We found that most tools are used by experienced scientists in a consultancy context, often associated with a research program. Most tools are of medium complexity and apply "cradle to farm gate" system boundaries. However, we found considerable heterogeneity in scope and methods, particularly for soil carbon fluxes. Furthermore, the necessity to consider consequential system interactions beyond the farm gate is recognized by most users. Results show that due to complexity and numerous methodological uncertainties, the assessment and interpretation of farm-level emission profiles is time-consuming and requires sophisticated tools and great expertise. Decision-making should be based on a set of indicators, thoroughly considering the goal and context of a project. Even then, a fair benchmarking and compensation system is challenging. Accordingly,

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accounting tools are rarely used for result-based reward mechanisms suggesting that their relevance for compensation mechanisms or emission trading is limited. Their strength lies more in awareness-raising and consultancy for mitigation actions. However, the estimated potentials at farm level of, on average 10–20 % GHG reduction, and the challenges associated with their MRV indicate that a purely technical approach at the farm level is currently insufficient to achieve the necessary GHG reductions. Our results thus point to the need for further capacity development and structural adjustments at a higher level in the agri-food system.

1. Introduction

Agriculture is affected by global climate change and simultaneously contributing to emissions of greenhouse gases (GHG), namely methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2; Bezner Kerr et al., 2022; Halpern et al., 2022; Nabuurs et al., 2022). The global food system is responsible for 21–37 % of total net anthropogenic GHG emissions (Crippa et al., 2021; IPCC, 2019a; Tubiello et al., 2021). To avoid exceeding planetary boundaries ambitious measures are needed to reduce these emissions (Clark et al., 2020; Costa et al., 2022; Rosa and Gabrielli, 2023).

Driven by growing societal awareness, stakeholders and administrative bodies are signing up for science-based targets (e.g., Deconinck et al., 2023; Richards et al., 2015) or setting policy targets (e.g., Henderson et al., 2020; Hönle et al., 2018) to minimize negative environmental externalities. In light of this, various measures and instruments have been developed to reduce GHG emissions from the agri-food system (e.g., Herrero et al., 2016; Roe et al., 2021; Searchinger et al., 2019; Springmann et al., 2018). Measures are available at different spatial scales. At the regional to national scale broader structural measures such as site adapted land-use and management may dominate whereas demand side measure can be located at the food system scale. At the farm level technical measures promoting production efficiency prevail. As these measures become implemented in practice the necessity for monitoring, reporting and verification (MRV) arises in order to demonstrate their effectiveness.

Farm-level GHG accounting tools allow to assess GHG emission profiles for farm-to-farm comparisons or ex-ante and ex-post estimations of GHG reduction potentials (e.g., Crosson et al., 2011; Hillier et al., 2016; Schils et al., 2007). Besides guiding decision making and efficient management, a reliable quantification of GHG reductions is also important for determining compensations for financial and other expenditures. Hence, stakeholders from the private sector and from farmers organisations often mention result-based reimbursement of mitigation costs as a motivation for farm GHG assessment (e.g., Lengers et al., 2013; Vellinga et al., 2011; Vermont and De Cara, 2010). As compared to other policy instruments where specific mitigation measures are promoted, GHG accounting tools are intended to allow for result-based compensation, offering more flexibility in meeting goals (OECD, 2023; Radley et al., 2021; Kreft et al., 2023). However, this may involve significantly greater complexity and considerably more effort. The distinction between a result-based and a measure-based compensation is thus widely discussed (e.g. Deconinck et al., 2023; Kreft et al., 2023; Radley et al., 2021). Project developers need to find a balance between fairness and efficiency and mediate between different interests amongst the participating farmers and the financing entity.

Following the necessity for more sustainability in the agri-food sector and the related policy developments, there is thus a constantly growing demand for GHG accounting tools. To provide reliable and meaningful results, these need to fulfil several quality criteria, comparable to the TACCC principles applied under the UNFCCC (Transparency, Accuracy, Consistency, Comparability, and Completeness; UNFCCC, 2018). The accuracy of emission assessments and the degree in which results are representative for the local context are closely linked to the complexity of the models used. Farm-level GHG accounting tools vary in complexity, ranging from simple multiplication of activity data with emission factors (Tier 1) to simple empirical models (Tier 2), and finally to more complex mechanistic modelling frameworks (Tier 3) (Greenhouse Gas Protocol, 2015; IPCC, 2006). Typically, system boundaries comprise all on farm activities to produce either specific products or the whole farm output. However, the repercussions of activities of a farm extend beyond the immediate physical perimeter of the respective land area. Emissions associated with the production and transport of means of production are referred to as pre-chain emissions. A scope that accounts for all activities from the manufacturing of all means of production until the point where farm products are sold to the primary purchaser is called “cradle to farm gate”. Scopes that also include transport, processing, retailing and consumption of food are referred to as “cradle to retailer” or “cradle to fork”, respectively. Transparent and consistent system boundaries are necessary to ensure the comparability of results from different approaches.

Additional to the rather linear concept of system boundaries along the value chain, there are further repercussions beyond the actual farm boundaries such as effects on neighbouring farms and other actors of the food system that may be affected by on farm decisions. These system interactions are generally treated in consequential life cycle analysis (Brander, 2022; Rajagopal, 2014). Consequential methods aim to provide information on the system-wide or global impacts caused by actions (Brander, 2022). Land occupation and use of biomass that compete with other uses of these resources are amongst the most important of these system-wide repercussions. When deciding on how to use limited land resources, the choice between the production of food and feed is most relevant (Mottet et al., 2017; Röös et al., 2016; Schader et al., 2015; Van Zanten et al., 2018). The overall efficiency of food production depends largely on how much arable land is dedicated to the production of livestock feed rather than food for direct human consumption. These system interactions are not directly visible when limiting analysis on the GHG profile of a single farm or product. E.g., by feeding more feed concentrates from arable land to dairy cows, farm GHG footprints per litre of milk may be lowered. However, global production efficiency in terms of calories and proteins decreases significantly, creating a discrepancy between the farm and the food system perspective (e.g. O’Brien et al., 2015). In addition, land and biomass may be used for the provision of bioenergy, further affecting the global net GHG balances by substitution of fossil fuels (Hertel et al., 2013; Muscat et al., 2020). Failure to address GHG emissions as a global problem could thus lead to undesirable developments (Franks and Hadingham, 2012).

Closely related to the topic of system boundaries is emission leakage, which occurs when improvements in one location cause deteriorations elsewhere beyond the system boundaries (Henderson et al., 2018; Müller, 2014; Peters, 2008). Internal leakage effects occur where incentives motivate farmers to focus reduction measures, onto specific fields or livestock activities while reducing efforts elsewhere on the same farm. External leakage effects arise where mitigation activities motivate farmers to exploit resources that are either not considered by an accounting tool and/or that lead to reduced supplies for other farmers. A prominent example for this is the lateral shift of biomass (e.g., as compost or manure) that may lead to an increase of soil organic carbon on the target farm but to lower carbon stocks in the place of origin (e.g., Paul et al., 2023). Furthermore, when mitigation measures reduce yields, they may contribute to land-use intensification or indirect land-use change elsewhere in order to counter the supply-demand imbalance (Flysjö et al., 2012; Hedal Kløverpris et al., 2010; Persson et al., 2014; Treu et al., 2017).

Other important components of agricultural GHG accounting are changes in carbon stocks in soils and biomass (e.g. agroforestry, hedgerows; Moinet et al., 2023; Morais et al., 2019, Vermeulen et al., 2019). Soils and biomass can both loose or gain carbon possibly leading to a net CO_2-increase or decrease in the atmosphere. Permanence and saturation are important aspects of carbon sequestration (Moinet et al., 2023; Smith, 2014). The removal of CO_2 from the atmosphere needs to be permanent to develop its full potential (Leifeld and Keel, 2022). Additionally, after reaching a new point of equilibrium no more carbon may be removed by a specific measure, while additional emissions related to a change in management may continue. A careful consideration of carbon stock changes and possible emission leakage is thus important to ensure the completeness of any GHG balance. A complete and comprehensive assessment should encompass all direct and indirect effects, whether this is done by a GHG accounting tool itself or through additional considerations in the overall context of a project.

Accurate and consistent results of farm level GHG accounting and their careful interpretation are necessary to guarantee a fair compensation for expenses and services rendered. In this context, the functional unit in which environmental performance is measured is decisive for a sound assessment of sustainability and for guiding efficient decision making (e.g. Frehner et al., 2020; Franks and Hadingham, 2012). In order to combat climate change, absolute emissions must fall, and efficiency gains must thus lead to a reduction of the associated resource usage (e.g., the cattle herd should be reduced when the milk yield per dairy cow increases). At the same time relative metrics, i.e., metrics that assess emissions in relation to a functional unit of production or a unit of an input or a resource, are needed to assess efficiency in production processes. Once the appropriate unit(s) and metric(s) are identified, different farms and their activities can be compared and/or the development of farms over time can be monitored. Benchmarking systems are then often used as the foundation of (financial) compensation and reward mechanisms. However, to understand the differences in emission profiles between farms or different points in time, the underlying drivers should be identified. This is not trivial since indicators for GHG emissions are both influenced by management decisions as well as by "external" factors that are not under the control of the farmer. Most importantly, farms differ in their emission profiles and in their mitigation capacities according to (i) the type of activities (e.g. livestock vs. crop production), (ii) their site conditions (e.g. lowland vs. mountain areas or moist vs. dry climate conditions), (iii) their socioeconomic environment and (vi) according to their efforts towards sustainability in the past (Clark and Tilman, 2017; Hutchings et al., 2020; Lesschen et al., 2011). Due to this multi-causality, it is difficult to quantify the specific impact of definite mitigation efforts made by a farmer, particularly in an ex-post assessment (Zosso et al., 2024).

Lack of standards and transparency, e.g. regarding the TACCC criteria, reporting units or benchmarking systems, is seen as one of the major barriers for the development of solid compensation mechanisms and for farmer's commitment for climate change mitigation (Bispo et al., 2017; Deconinck et al., 2023). Such a situation is particularly unsatisfying when environmental performance is subject to compensation payments, premium prices or eligibility for label programs. For this reason, agricultural GHG offset mechanisms have been criticised repeatedly as being inefficient or even counterproductive (e.g., Böhm and Dhabi, 2011; Gillenwater, 2012) particularly in the context of soil carbon sequestration (Müller, 2014; Oldfield et al., 2022; Paul et al., 2023). Accordingly, regulative standards, protocols and guidelines have been developed in the past (Deconinck et al., 2023; Gillenwater, 2022). Most accounting tools ultimately rely in some form on the IPCC Guidelines for national GHG inventories (IPCC, 2006; IPCC, 2019b) and thus share a common yet insufficient basis. Public and private institutions and international initiatives are trying to fill this gap (see list of protocols, standards and guidelines in supplementary materials). Guidance and standards can be grouped in: (i) technical aspects concerning the calculation models (e.g., the IPCC Guidelines) and (ii) issues concerning the broader framework of GHG accounting such as scope and system boundaries, leakage or handling of uncertainty and (iii) issues related to the use of results in mitigation claiming, GHG footprint declarations and carbon trading and offset mechanisms. The latter comprise particularly additionality of mitigation measures, permanence and saturation of carbon sinks and benchmarking approaches for farm comparisons.

A thorough elaboration of GHG accounting tools and a clear guiding framework for their application are important to identify suitable mitigation options. However, past research has shown, that once mitigation measures have been defined, various barriers may hamper their implementation in practice (Fleming et al., 2019; Sánchez et al., 2014; Smith et al., 2007). Financial constraints may be decisive. Yet, many marginal abatement cost analyses in the past found considerable mitigation potentials at negative costs (i.e., implementation would lead to higher incomes). The fact that the respective measures have not yet been implemented in practice, therefore suggests that also non-monetary constraints are substantial (e.g., Kreft et al., 2023; Moran et al., 2013). Furthermore, when GHG reduction measures are subject of compensation benefits, the effect of the reduction measure must be additional to what would have happened without the respective incentive (Oldfield et al., 2022; Paul et al., 2023). For instance, some measures may be part of cross-compliance requirements under a policy framework and thus lack the necessary criteria of additionality for mitigation claiming by others. To assess additionality, a scenario with a GHG reduction measure should thus always be compared to a counterfactual business-as-usual-scenario. These topics have been rather underrepresented in the scientific literature and insight from application of accounting tools in practice may shed light on these matters.

So far, farm-level GHG accounting tools have been mainly used in scientific modelling exercises (e.g., Crosson et al., 2011; Colomb et al., 2013; Whittaker et al., 2013). While first experiences are being gained applying these tools in practice (e.g. Beukes et al., 2011; Christie et al., 2011; Sykes et al., 2017; Tuomisto et al., 2015;), GHG accounting is still in its infancy and we do not have a clear picture of associated policy implications or consequences for emission trading, product labelling or localisation of responsibilities. Based on the current state of farm-level GHG accounting and the multitude of related challenges we hypothesize that the current landscape of diverse whole-farm accounting tools has limited potential to support compensation mechanisms and/or emissions trading. In this study we thus further investigate how the above-mentioned challenges are handled in farm-level GHG mitigation projects in practice. Thereby our study aims to supplement the rather theoretical findings on farm-level GHG reporting to date by exploring experience gained from real life application. Based on our findings, we explore the prerequisite for delivering reliable and meaningful results for decision makers, ensuring compliance with the TACCC principles. Specific recommendations shall support the further development of guidance and standards for GHG accounting and mitigation action at the farm level (see supplementary material for a concise list of recommendations). Based on an online survey of practical experiences with farm-level GHG accounting tools in 30 projects worldwide we are seeking insight into the following questions:

- Who is using what kind of farm-level GHG accounting tool in which context for agricultural GHG mitigation in practice?
- What results are generated for what purpose? How are they used, displayed and communicated?
- For what purpose and in what context can farm-level GHG accounting tools be recommended and what are the most important limitations encountered when applying them in practice?
- What is the potential for reducing agricultural GHG emission and how can tools and their usage be improved to promote GHG mitigation?

2. Materials and methods

In order to investigate our research questions, an online survey on farm-level GHG accounting tools was conducted. Our analysis does focus primarily on the responses to the survey. In depth analysis of the individual tools, their source codes and the respective manuals and documentations was beyond the scope of this assessment. Responses to the survey were analysed by descriptive statistics. Eventually cross comparisons across different questions were made and if possible "correlations" were analysed to check for plausibility and to gain further insight.

Additionally, an assessment of the general state of knowledge in farm-level GHG accounting was conducted and the specific findings of the survey are compared to the scientific literature and discussed accordingly. For this purpose, peer-reviewed publications as well as selected reports and papers from the grey literature were reviewed (see supplementary material for a more extensive list of references).

2.1. Structure and addressees of the survey

The online survey on farm-level GHG accounting tools contained ten sections with 4–10 questions each. Most questions were multiple-choice, requiring either one unique answer amongst several options or allowing for multiple selections. Other questions could be answered by "yes" or "no" and eventually "don't know". Only few questions required answers in plain text. However, addressees had the opportunity to provide further comments to specify or clarify their answers. If a respondent did not choose any answer option of a multiple-choice question, an answer based on their comment was chosen if applicable. Some questions had fewer respondents than the total number of projects or tools in the dataset, as the specific activities apply only to some of the tools or projects. This concerns particularly all questions relating to carbon sequestration and questions in the sections on "Reward/accreditation mechanisms" and "Results". For a complete list of the questions, the possible answers and the number of tools and projects providing respective information, the reader is referred to the supplementary material. As far as possible we tried to apply the same wording, specifications and examples in this paper as were used in the questionnaire.

Before the official launch of the survey a pre-test was conducted on five selected candidates. According to the identified shortcomings and problems, specifications and adjustments were made. Subsequently, the survey was conducted from February to July 2022. A call for participation was sent to chosen addressees worldwide. People involved in regional networks (e.g. TheKLa in German speaking countries, Carbon Farming initiative in Europe (Radley et al., 2021), Asia-Pacific and Australia networks (e.g. Asia-Pacific Integrated Model) or global networks (Global Research Alliance on Agricultural Greenhouse Gases, GRA) were asked to forward the call to suitable organisations and colleagues. The questionnaire should be completed by people directly working with farm-level GHG accounting tools in practice. In a cover letter it was emphasised that the tools should be applied in mitigation projects that aim to identify and assess (theoretical) emission reduction potentials on commercial farms (see cover letter in supplementary material). The answers in the questionnaire should refer to one specific GHG accounting tool in the context of one specific project. Projects that use GHG accounting tools for purely theoretical studies in research should not be part of the survey. Respondents were asked to focus on their personal experience and judgement rather than on hard and scientific data if they were unsure about the adequacy of their answer. Completion of the questionnaire should take no more than one hour and could be interrupted and resumed at any time. In order to assure honest and authentic answers, confidentiality was assured. Accordingly, the results are published in a way that prevents conjunction of specific responses with individual projects and tools.

2.2. Total number of respondents, tools, projects and farms

Overall, 43 respondents participated in the survey. 13 were excluded due to incompleteness and limited information. The selected 30 responses correspond to 30 different GHG mitigation projects that cover 23 different farm-level GHG accounting tools, as some tools are used in more than one project. However, some respondents did not strictly follow the requirement that the answers should refer to one specific GHG accounting tool in the context of one specific project. In these cases, answers may refer to the general application of a tool across various projects, which means that the number of projects covered may be higher than 30. Still, for our analysis we assume that responses to questions concerning the implementation and use of a tool in a specific mitigation project (including questions concerning the users) relate to a total n of 30. Questions related to the nature and properties of the tools equals 23. For some sections on presentation and communication of results and compensation mechanisms as well as on estimated and achieved emission reductions the total n is reduced by one (i.e., tools: 22, projects: 29) as one respondent did not finish the whole questionnaire. See supplementary material for the subject (project, tool) for each question and the corresponding number of possible respondents (n).

Respondents indicated the number of farms covered by their specific project by selecting from various size-classes. For a rough estimate of the total number of farms covered by the survey we multiplied the number of counts of a size class with the mean number of farms of this size class (e.g., size class 200–500 would correspond to 350 farms). For the highest size class ($> 10'000$) an upper limit of 20′000 farms was set. This yields a total of 40′000 farms covered by the 30 projects.

Different users of the same tool did not always respond consistently when asked for specific properties of their tool. This may be due to different versions of a tool. However, it may also indicate that a question can be applied both on the property of a tool or on the characteristics of a project. For instance, if asked whether there is an economic assessment of farm operations, such an assessment might be done automatically within the accounting tool itself or independently within the general context of the project. Whenever possible we tried to consider these issues by interpreting the specific answer in the context of the complete data of a tool or project, i.e., by conducting cross comparisons between different sections and questions of the survey.

3. Results

3.1. Profiles of respondents and purpose and context of using GHG accounting tools

Although efforts were made to encourage participation of projects from low- and middle-income countries, almost 90 % of the 30 responses originated from industrialized, high-income countries. Two third of the survey participants are from Germany, New Zealand, the United Kingdom and the USA. Four respondents are from Africa and no answers were received from Latin America and Asia.

Most respondents hold a position in research mainly in the field of modelling (Fig. 1). Almost 60 % are involved in some form of consulting or education services. Only a few respondents ($<$15 %) are farmers or working for a farmer's organization. According to the professional position, 90 % have a background in natural science or agronomy while a background in economy and/or farming was indicated by 23 and 17 %, respectively. Over 70 % have $>$5 years of practical experience in the field of (agricultural) GHG emission accounting and 20 % even exceeded 15 years of experience.

GHG accounting itself is mainly conducted by a "Scientists/researcher" (17) or an "Advisory service" (13) (Fig. 2). "Farmers" was chosen by 9 respondents, however, always in conjunction with one of the other possible answers mainly "Scientists/researcher" and "Advisory service" or "Farm extension service".

The main purposes of farm-level GHG accounting are "Awareness-

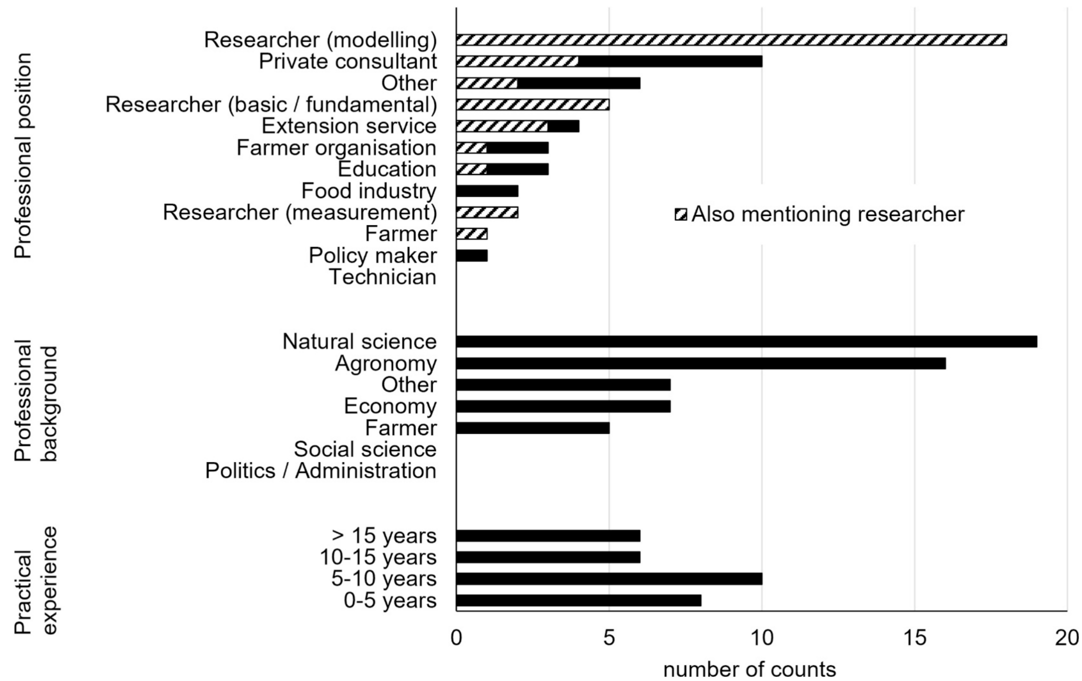

Fig. 1. Professional position, professional background and practical experience of respondents to the survey on farm-level GHG accounting tools.

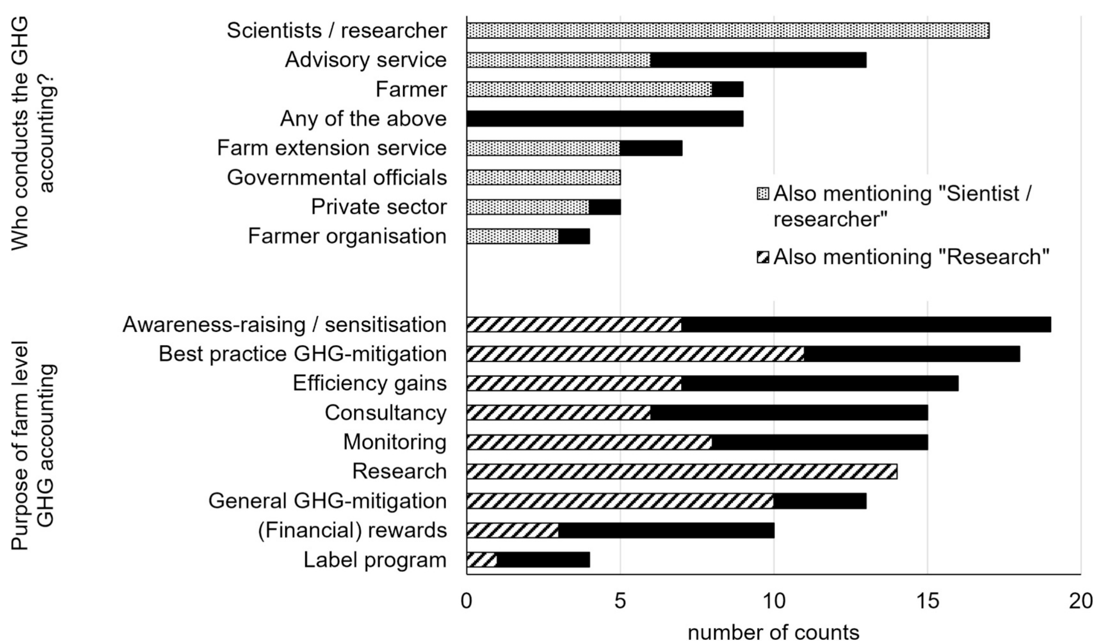

Fig. 2. User of the GHG accounting tools and purpose of farm-level GHG accounting.

raising/sensitization" (19) and "Best practice GHG mitigation" (18). "Efficiency gains" (16), "Consultancy" (15), "Monitoring" (15) and "General GHG mitigation" (13) were also frequently selected. Almost half of the projects are related to research and in three cases this was the only purpose. The purpose of (financial) rewards was indicated for one third of the projects. Notably, this answer was never chosen alone but always in combination with other purposes.

More than half of the 30 projects are connected to governmental initiatives and three quarters of these projects indicated a governmental-private sector partnership (Fig. 3). Half of the respondents indicated that projects are connected to research programs or are even pure research projects. Only four projects seem to be solely based on initiatives of the private sector (food industry or farmer's organization) and two of them are connected to research programs. Moreover, 60 % of the projects are part of a national and/or regional agricultural low emission strategy. 6 of the 30 participants indicated that GHG accounting is financially incentivized but only one respondent specified that accounting is mandatory for receiving subsidies. Six respondents pointed out that GHG accounting is part of a national/regional carbon offset program.

3.2. Scope, complexity and methodologies of the farm-level GHG accounting tools

16 of the 23 tools were classified as "Fully integrated whole-farm

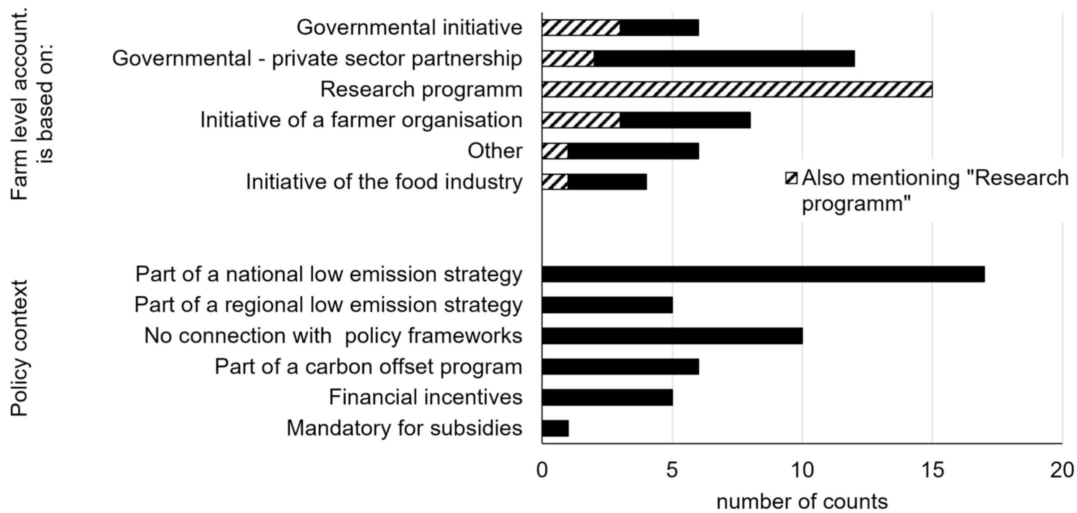

Fig. 3. General and political context of farm-level GHG accounting.

models". Most of the remaining tools and projects focus on livestock only and one tool is specialized exclusively on plant production. Comments indicated that several tools may be used within one project with each tool covering specific activities. Besides GHG emissions, "Nitrogen balance/nutrient management" (20), "Energy use" (15) and "Land use" (12) are considered most frequently. "Water use/freshwater quality", "Pesticide use" and "Biodiversity" were selected 6, 6 and 5 times, respectively. One comment mentioned additionally "Humus balance, Soil erosion, Soil compaction". Moreover, 10 out of 23 tools conduct an economic assessment.

For 8 and 13 of the 23 tools, system boundaries were classified as "On site/farm emissions only" and "Cradle to farm gate", respectively (Fig. 4). Only two tools apply "Cradle to retailer" system boundaries and none "Cradle to fork". In agreement with this, 10 respondents explicitly specified that pre-chain emissions are considered, with emission from the production of fertilisers (8) and livestock feed (7) mentioned most frequently. Notably, four respondents indicated "Cradle to farm gate" system boundaries but reported that pre-chain emissions are not considered. Furthermore, a vast majority of the tools, i.e., 20 out of 23, has no specific assessment of possible emission leakages.

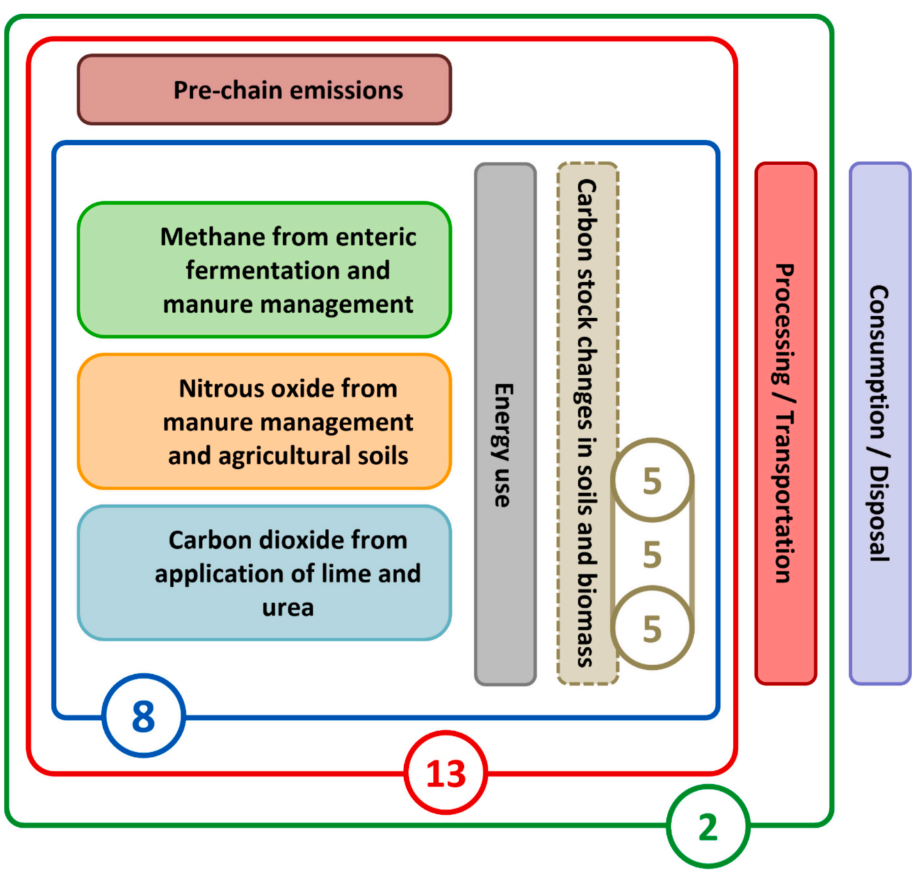

Fig. 4. System boundaries applied by farm-level GHG accounting tools covered by the online survey: Blue: "On site/farm emissions only", red: "Cradle to farm gate", green: "Cradle to retailer". Dashed line: "Carbon stock changes in soils and biomass" may be considered or not independent of the overall system boundaries.

According to the survey 8 of 23 tools do not account for carbon sequestration in soils and/or biomass (Table 1). 10 consider for soil carbon sequestration, 6 using a Tier 1 approach and 3 a process oriented biogeochemical model. 5 of these tools additionally account for carbon sequestration in biomass. 5 tools include accounting of carbon in biomass only. Some comments indicate that carbon sequestration in soils and/or biomass is considered in the projects independently from the farm-level GHG accounting tool by using additional methodologies.

8 of the 10 tools that account for soil carbon sequestration consider land-use history. Amongst the 15 tools accounting for carbon sequestration in soils and/or biomass, only 5 tools clearly account for possible saturation effects. Most consider non-permanence of carbon sequestration in some way with only 3 negative answers. Furthermore, only 3 responses affirmed that possible leakage effects due to mere lateral transfer of carbon are explicitly considered. Notably, several respondents selected the option “don’t know” for questions concerning carbon sequestration.

Regarding the extension of the scope of the tools via integrating consequential system interactions the replies indicated that 8 tools are considering feed-food (1) or land-use competition (1) or both of them (6) (Fig. 5). Additionally, 13 out of 30 respondents affirmed that “The farm-level GHG accounting is embedded/accompanied in/by a national/regional land-use strategy” and 4 affirmed a corresponding biomass strategy”.

11 out of 23 tools are of medium complexity applying a Tier 2 approach (Fig. 6) with Tier 1 and Tier 3 being selected 3 and 5 times. When asked for the requirements for using the tools, for 13 a higher university degree or a special training is needed. Notably, it was commented that although officially no special requirements or formations may be needed, some training is needed in order to “know how to deal with the results”.

Respondents indicated that 10 tools are fully and 11 are partially adapted to national/regional site conditions with only two largely based on generic default parameters. Comments indicate that in various cases, generic tools have been adjusted to the specific and/or local circumstances. In this context, survey results show that for 16 out of 23 tools users can replace default factors/parameters when more specific values are available (e.g., from measurements, local empirical values). A distinction between influencing factors of (i) local site conditions (climate, soil, topography) and (ii) farm management (i.e., actions that are directly under the control of the farmer) is possible for less than half of the tools (10 of 22). These tools are usually of higher complexity, adapted to local site conditions and/or allow for site specific parameterisation.

About half of the 23 tools integrate one or more existing databases and IT-systems, with “use of national administration databases” being the most common (8). Some tools use land-use maps (4), soil maps (5) and meteorological data (5). The use of remote sensing data was only selected once. Several survey participants commented that their tools are not yet automatically linked to external data but that they are working on it.

Most tools (17 of 23) do not assess and report uncertainties and 16 of 23 do at least partially assess data quality. However, only one of these replies clearly affirms the presence of an automatic data quality assessment. About half of the 23 farm-level GHG accounting tools are freely available online, with 4 requiring registrations.

3.3. Presentation and communication of results

Answers in respect to the reporting units were provided by 29 respondents covering 22 tools. Virtually all tools provide results on emissions as total CO_2-equivalents (27) and by type of GHG (23) (Fig. 7). Comparisons of emissions to e.g., a base year (emission reductions) or to a benchmark were selected 11 and 10 times, respectively. Most tools and/or projects report GHG efficiencies. The most used units are CO_2-equivalents per kg of product (21) and per land area (19). Emissions per human digestible energy (e.g., calories) or proteins were chosen only 2 and 8 times, respectively. CO_2-equivalents per economic gain are assessed in only three projects using two different tools.

Regarding the allocation of the emissions to different processes and/or activities, almost everybody (26) chose the answer “Per emission source / sink category”. About half of the respondents chose one or several additional options, mainly “Per farm activity / sector” (15), “Per crop culture, livestock species” (14) and “Per product” (17). “Per geographical region” was chosen 4 times. Concerning the type of emission allocation, 12 out of 23 tools allocate emissions according to the amount of product in kilograms (biophysical allocation) whereas economic allocation and allocation per energy/protein apply each for 6 tools. Only three respondents indicated no allocation.

In 23 of 29 projects results are presented as “Farm-level report”. When the option “Farm-level report” was not selected, this was typically because the results were mainly used for research. Accordingly, the option “scientific report” was chosen 9 times. “Company-report, report of an association” (6), “Exact numbers on product packaging (e.g., kg CO_2 eq.)” (3) and “Advertisement, general marketing strategy” (1) were less common. The options “Product label” and “Best in category” were not selected.

3.4. Benchmarking systems and compensation and reward mechanisms

The modelling of possible mitigation measures may be an integral part of the tools or conducted by running different scenarios. In 8 out of 30 projects there is no immediate connection to mitigation measures. In the remaining 22 projects possible measures are considered through: an “(Open) list of possible mitigation measures” (10), and/or an “Automatic suggestion of specific mitigation measures” (4) and/or an “(Automatic) scenario analysis” (5). 8 tools do calculate reduction potentials automatically. Finally, 7 respondents indicated that GHG accounting is connected to consultancy and farm extension services where mitigation options can be explored.

In order to compare productivity and/or sustainability of farms a benchmarking system is needed. For 10 out of 29 projects there is no benchmarking system (Fig. 8). Others specified that the benchmarking system is either based on “best practice” (2), “national/regional averages” (4) or “national/regional averages subdivided by farm-type/production system” (6). A temporal benchmarking system, i.e., comparing GHG emissions in a given year with emissions in a base year, was selected 7 times.

Table 1
Accounting of carbon sequestration (CS) in soils and biomass and consideration of land-use history, saturation effects, non-permanence and possible leakage due to inputs of external carbon.

		Consideration of:										
		Land use history		Carbon saturation			Non-permanence			Leakage due to external carbon		
No accounting of CS	8	Yes	No	Yes	No	Don’t know	Yes	No	Don’t know	Yes	No	Don’t know
CS approach / model unknown	1											
Soils: Tier 1 model	6	8	2	5	6	4	10	3	2	3	10	2
Soils: Process oriented biochem. mModel	3											
Biomass (e.g. agroforestry, hedgerows)	10											

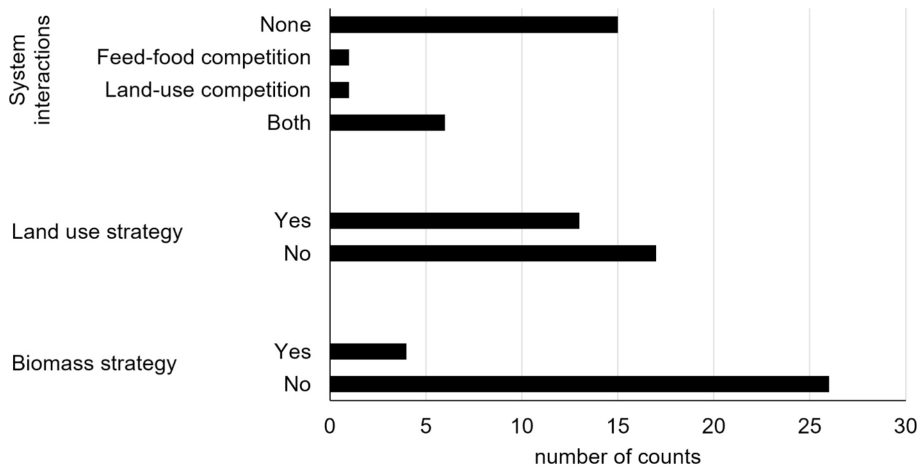

Fig. 5. Consideration of consequential system interactions in farm-level GHG accounting.

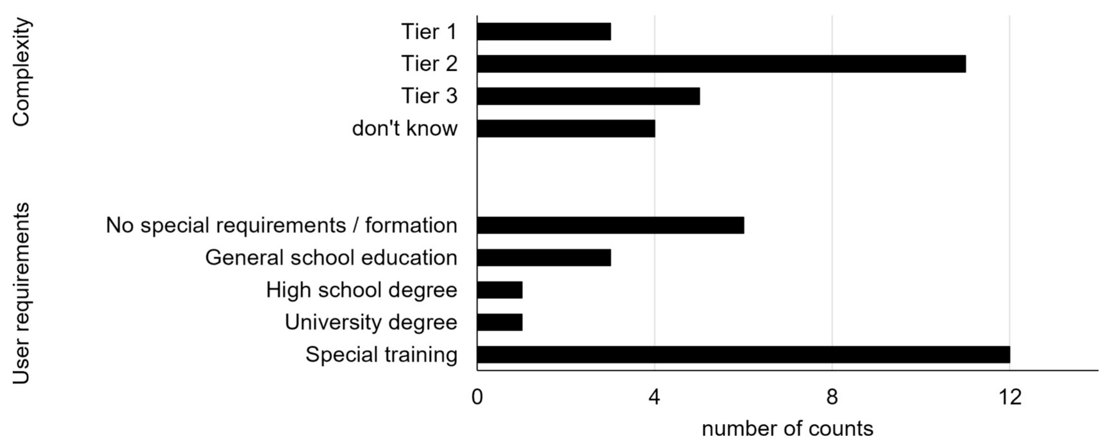

Fig. 6. Complexity and user requirements of GHG accounting tools covered by the survey.

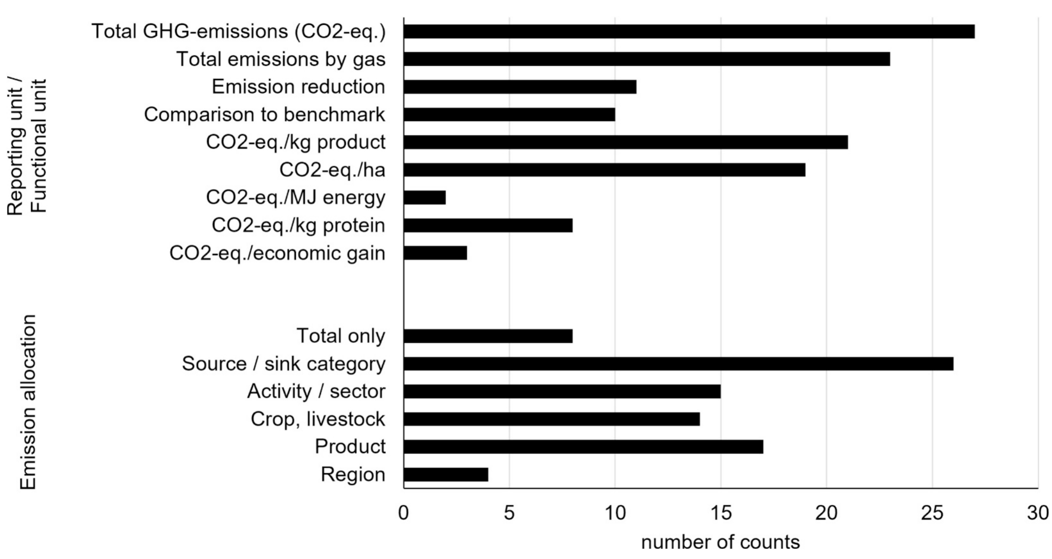

Fig. 7. Reporting units and emission allocation used by farm-level GHG accounting tools.

Payments for GHG mitigation may be an important motivation for farm GHG assessments. However, 25 of 30 projects indicated that there was no reward mechanism connected to the farm-level GHG accounting. Amongst the 5 projects that had a reward mechanism, respondents specified that the reward is "directly related to emission intensity" (2), "directly related to emissions of CO_2-equivalents" (1) or "measure-based" (1). All 5 projects indicated that the reward/accreditation mechanism is linked to some kind of financial incentive, either directly

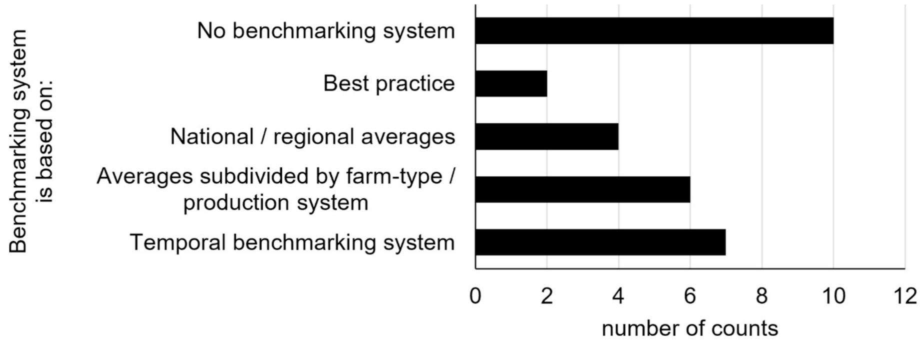

Fig. 8. Benchmarking systems used in farm-level GHG accounting projects.

(2) or in form of "Higher market prices" (4) or "Carbon-offset mechanism" (2). Finally, 3 of the 5 projects affirmed that the reward mechanism is adjusted according to: "Uncertainties of emission reductions" (2), and/or "Reservations about additionality" (1) or "Non-permanence (e.g. buffer allowances for eventual soil organic carbon losses)" (1).

3.5. Estimated and achieved emission reductions

In most projects the number of farms analysed was between 10 and 200. 5 projects analysed more than 1′000 farms and of these, two more than 10′000 farms. 23 projects provided an estimate of the "theoretical GHG reduction potential (i.e., without considering costs and other implementation barriers)" covering approximately 20′000 farms. For 19 projects, the theoretical reduction potential was estimated to be higher than 15 %, and for 5 higher than 30 % (Fig. 9). An estimate of the "practical reduction potential (i.e., considering costs and implementation barriers)" was provided by 22 projects. Most projects estimated a practical potential of 10–15 %. Notably, for 13 of the 22 projects, the difference between the theoretical and the practical reduction potential was 10 % points and more. Effective reductions achieved in practice were reported for 18 projects, lying mainly in the ranges of 5–10 % (6), 10–15 % (3) and 15 to 20 % (6). Only two respondents reported effective emission reductions of more than 30 %. For 10 out of 16 projects that reported both the theoretical potentials and potentials effectively realised, the difference between the two estimates was 10 % points and more.

3.6. Challenges, barriers and priorities for further development

Survey participants were asked to select possible challenges encountered when using the farm-level GHG accounting tools. This question was answered for 29 projects, with "Time consumption" being the most frequently selected option (18). Other frequent challenges were "Unreliable input data/no quality control" (14), "High complexity" (12) and "Standard values not appropriate for local conditions" (12). User-friendliness, respectively the lack of it, was selected 6 times. Time constraints, high complexity and lack of user-friendliness were also frequently mentioned by users with more than 10 or 15 years of experience in the field of agricultural GHG emissions.

Concerning the challenges and barriers for implementation of identified emission reduction measures on the farms, 29 respondents could choose multiple answers amongst 6 options. "High costs" (16) was chosen most often followed by "Lack of know-how" (14), "Lack of awareness" (13), "Time constraints" (12), "Organisational constraints" (10) and "Social/cultural constraints" (8). In addition to this, it was commented more than once that the lack or the uncertainty of financial compensation is a major obstacle when implementing emission reduction measures.

Survey participants were asked what would "make farm-level GHG accounting more attractive for the relevant stakeholders" and "what is needed to make farm-level GHG accounting more effective and operational in practice". Financial or other compensations (10) and more user-friendly and less complex and time-consuming tools (8) were

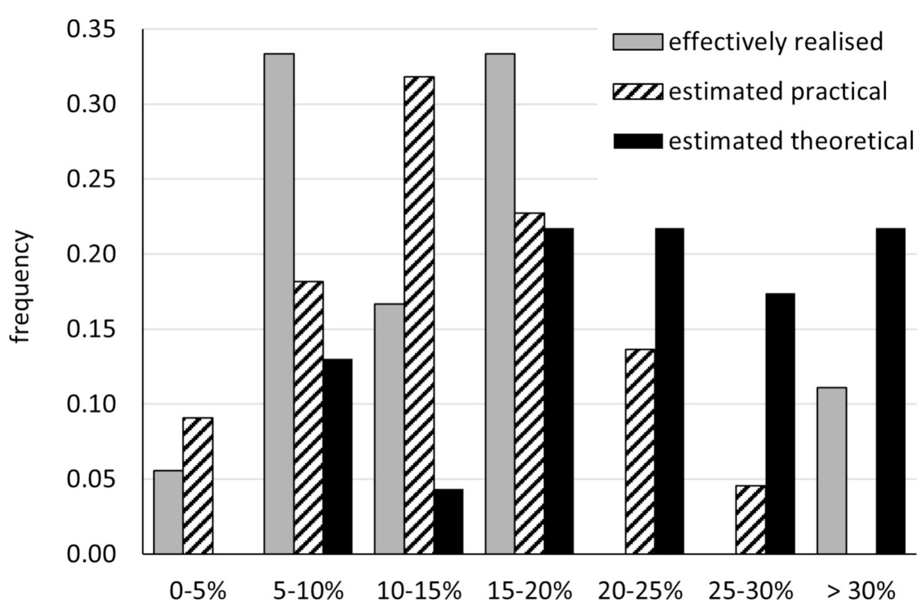

Fig. 9. Comparison of estimated theoretical ($n = 23$), estimated practical ($n = 22$) and effectively realised ($n = 18$) GHG reduction potentials in agricultural climate protection projects.

highlighted as the main options. Integration with existing data recording software to reduce complexity (8) as well as standardized protocols (3) were also frequently mentioned. Other suggestions were the promotion of awareness and know-how e.g., via consultation as well as better access to appropriate tools. In addition, respondents suggested to promote demo-farms and other means to highlight the achieved environmental benefits.

Farm-level GHG accounting is only one amongst various possibilities to promote climate friendly agriculture. Amongst other promising options to promote climate friendly agriculture in practice survey participants most frequently mentioned capacity building and training (7), often combined with the promotion of farm extension services (4). Higher prices (3) and other financial incentives (4) were also prominent replies. Technical advances were mentioned as a general pathway, or in the form of specific measures. Furthermore, the promotion of consistent and integrated policies and regulations along the whole food chain and particularly the promotion of an enabling environment were prominent amongst the suggested solutions.

4. Discussion

4.1. Scope and system boundaries of GHG accounting tools and importance of consequential system interactions

Most tools in the survey are whole-farm tools. Tools with only partial coverage focus mainly on livestock farming reflecting its great significance for GHG emissions (Gerber et al., 2013; Reisinger et al., 2021; Halpern et al., 2022). Moreover, many tools include assessments of other environmental aspects with nitrogen balance/nutrient management and energy use being the most frequent, due to their direct linkage to GHG emissions (nitrogen: e.g., Snyder et al., 2009; energy: e.g., Lal, 2004). Energy use in food supply chains includes fertilizer and equipment manufacturing, on farm energy use for machinery and heating, industrial food processing, packaging, refrigeration, and retail. Compared to reducing this energy use, a greater potential may lie in improving nutrient management thereby reducing nitrogen fertilizer input. This would not only reduce field N_2O emissions but also GHG emissions from fertilizer manufacturing. Several studies found that increasing the overall nitrogen-use efficiency is a very effective strategy to reduce agricultural GHG emissions (Gao and Cabrera Serrenho, 2023; Gerber et al., 2016).

Although most tools cover all activities from cradle to farm gate the issue of system boundaries remains controversial. A considerable share of the tool's neglects pre-chain emissions, which can represent a substantial share of emissions (i.e., 10 to 50 %), particularly when large amounts of synthetic nitrogen fertilisers or feedstuff are purchased (e.g., Hillier et al., 2011; Schils et al., 2007; Sykes et al., 2017). Furthermore, post farm gate emissions (food processing and packaging and transportation) became more important in recent years (Tubiello et al., 2022). In fact, Lewis et al. (2013) as well as Sykes et al. (2017) found that differences scopes and particularly different assessments of so-called scope 3 emissions can explain a large amount of the variation in estimated total farm GHG emissions. Additionally, our survey results indicate that users may not always be fully aware of the exact scopes of their tools, and possible emission leakage is rarely assessed. This means that particularly inexperienced users may not be aware of possible repercussions of farm operations on processes beyond the system boundaries. These constraints limit the validity and utility of the results from accounting tools. Additionally, it makes comparison between different tools a challenge. In a recent report by DEFRA in the UK the authors found that emissions estimates differed by up to 1000 % when applying six different GHG accounting tools on a set of 20 model farms (DEFRA, 2023).

Closely related to the subject of system boundaries is the question whether carbon fluxes and eventual carbon sequestration in soils and biomass are included in the overall GHG balance or not. More than half of the tools included in the survey do not account for carbon sequestration in soil and/or biomass and thereby miss important components of a whole-farm GHG balance (e.g., Bolinder et al., 2020). Colomb et al. (2013) and Lewis et al. (2013) identified failure to account for emissions due to land-use change as one of the main limitations of agricultural GHG assessments. Furthermore, land-use history, permanence, saturation effects and carbon leakage need to be considered in order to receive a complete and reliable assessment of the climate impact of carbon stock changes (e.g. Guillaume et al., 2022; Ogle et al., 2023; Paul et al., 2023). Although some tools take into account some of these issues, it is not always apparent from the survey results, whether these aspects are considered implicitly in the calculation routines, during data entry or in the overall project framework. In various cases the respondents themselves do not even know if and if yes, how certain mechanisms are implemented. Together with the general uncertainties that are connected to the assessment of carbon fluxes (e.g., Keel et al., 2017; Ogle et al., 2003) this calls for additional caution. These findings are in line with other studies such as e.g. Lewis et al. (2013) who found that approaches for carbon sequestration are very different across tools and that results can be highly variable and uncertain. The many unresolved issues may thus explain restraints to integrate carbon sequestration in farm accounting tools (Colomb et al., 2013; Lewis et al., 2013; Rubin et al., 2023). A clearer framework for accounting carbon fluxes and carbon storage in soils and biomass (Ogle et al., 2023; Oldfield et al., 2022) in addition to the already existing regulations and standards is thus needed (Batjes et al., 2023; FAO, 2019; McDonald et al., 2023).

Agricultural farms are embedded in a complex land-use and food system landscape and on-farm decisions may have consequences beyond the immediate farm limits (e.g. Fuchs et al., 2020; Hedal Kløverpris et al., 2010; McNicol et al., 2024) not only including the biophysical but potentially also the socio-economic dimension (Jaisli et al., 2019; Paul et al., 2019). Thereby the competition for limited land resources (e.g. Schmidt et al., 2015) seems to receive more attention than the competition for different uses of biomass, although the latter may be equally important (Muscat et al., 2020). Our survey results suggest that certain system interactions and particularly land-use- and biomass-competition are only addressed in a minority of the projects. However, the importance of these aspects may be reflected by the fact, that the majority of the projects are linked to governmental or regional agricultural low emission initiatives and/or "embedded/accompanied in/by a national/regional land-use strategy". Accordingly, it may be argued that repercussions on processes beyond the farm gate do not fall under the responsibility of the farmers and/or the local project leaders and must be dealt with on a higher level. While this view is legitimate, we argue that as long as there are no overarching regulations that prevent undesirable developments, possible system interactions must be considered when taking on-farm decisions. Farm-level GHG accounting would thus benefit from additional indicators that address such issues as is done in consequential life cycle assessment (Rajagopal, 2014; Thomassen et al., 2008). For feed-food and land-use competition such indicators have been proposed by e.g. Wilkinson (2011) and van Zanten et al. (2016) and tested by e.g. Ineichen et al. (2023).

4.2. Complexity of GHG accounting tools, technical operational questions and uncertainties

The technical standard of the tools covered by the survey is high and goes much beyond simple Tier 1 approaches. Often calculation parameters are adapted to local site conditions and/or the user can parametrise the model himself. Many tools do integrate existing databases such as national administration databases, soil maps or meteorological data. These aspects are an important strength since they improve accuracy and assure that results are pertinent to the local context. Both local environmental site conditions as well as socio-economic and political contexts exert a strong influence on agricultural GHG emissions (Colomb et al., 2013; Dorich et al., 2020; del Prado et al., 2013; Olander et al., 2014). Survey results thus indicate that most users are aware of the need to adapt methodologies to local site conditions, which is only possible using more detailed and complex models. Nonetheless, accuracy remains an important topic and it is a matter of discussion whether there may still be systematic biases, particularly concerning soil GHG fluxes (Ellis and Paustian, 2024; Gaillard et al., 2018). Rainford et al. (2024) for instance demonstrated that humus balance calculators often poorly correlate with the observed changes in soil organic carbon contents from field measurements.

For the evaluation of results from farm-level GHG assessments and the identification of mitigation strategies the distinction between influencing factors that can or cannot be controlled by individual actors is important. While it is impossible or very difficult to control environmental conditions, technologies, management and agricultural structures can be governed. Controllable influencing factors can further be divided into structural factors and factors related to management and technology. Structural factors mainly impact activity data such as type and number of animals and crops. These parameters can be monitored by relatively simple tools, while changes in management and technology may be more difficult to capture, possibly going beyond the level of detail applied by most current tools. In this context it is noteworthy that many survey participants consider the current state of farm-level GHG accounting as being already too complex, time consuming and not user friendly. Notably, this is equally true for more experienced experts and experts from small projects with less than 200 farms.

The distinction between structural changes and changes of management and technology is also important when considering uncertainties. Most activity data and their changes can be determined accurately. Changes in emission profiles caused by structural changes have thus low uncertainties. Quite contrarily, when measures are designed to alter emissions factors via technical interventions, the related uncertainties are comparatively high. This is particularly relevant when assessing the effect of mitigation measures and the reliability of the associated emission reductions. Survey results indicate that most tools do not assess and report uncertainty systematically. Data quality assessment may be somewhat more advanced but is still considered an important challenge when using tools.

In general, aspirations for high data quality, accuracy and low uncertainty must be balanced against workload and cost of GHG accounting. Although plausibility checks can considerably improve data quality, they are time-consuming and usually still fail to capture all incorrect entries (Gilgen et al., 2023). Depending on the purpose, simpler tools that are driven by less, but more reliable and solid data may thus be preferred (e.g., Roesch et al., 2023). The overall purpose of a project and in particular the nature and design of the intended mitigation measures should therefore be considered carefully when selecting an appropriate accounting tool. Additionally, it is important that users are well aware of the existence of uncertainties and data quality issues, their origins and their significance for depicting small differences in farm structure and management (Colomb et al., 2013). The respondents to the survey have a relatively high level of education and at the same time they point out the high demands of users in this regard. It is therefore obvious that the practical application of tools and the meaningful interpretation of the respective results require a high level of expertise and experience.

4.3. Presentation and interpretation of results

The unit and/or metric in which measured or modelled data is reported can have a large influence on the interpretation of the results and the respective conclusions for further action (Frehner et al., 2020; Franks and Hadingham, 2012). Accordingly, the decision which unit to use largely depends on the policy context and ultimately on the type of the targeted intervention in the agriculture- and food-system. Before selecting a tool for a specific purpose, it should thus be clarified which routines are already integrated in the tools and which additional assessments must be conducted separately.

Overall absolute GHG emission of a farm in kg of CO_2-equivalents is most used. Most tools covered by the survey additionally report emissions by individual gases, allowing flexibility for aggregating long- and short-lived GHGs. This separate reporting supports thus an objective assessment of the implications of aggregated emissions for radiative forcing and global temperature (Allen et al., 2022; Lynch, 2019). Absolute emissions in kg of CO_2-equivalents are most useful when conducting ex-ante estimations of a set of specific technical reduction measures or comparing similar farms. Furthermore, total absolute emissions on a farm or within a project or region are needed to assess eventual rebound effects of a more efficient production (García et al., 2020; Murray and Baker, 2011; Paul et al., 2019). Amongst the relative metrics, emissions per hectare is a common unit that is, however, often of limited use as the amount of food (calories, proteins) produced per area varies considerably between different agricultural activities (Colomb et al., 2013; del Prado et al., 2010). Emissions per unit of production is equally widespread and usually more relevant, particularly in the context of food security (e.g., Murray and Baker, 2011). However, the exact measure in which “production” is expressed is relevant. Kilogram of product is the most used. Yet, different agricultural products have different nutrient contents and one kg of product can thus contribute differently to human nutrition (Drewnowski et al., 2015; Green et al., 2021). In this regard, Frehner et al. (2020) demonstrate how the choice of different functional units can result in different implications for policy makers. The survey results show that only eight tools provide results per calories and/or proteins. Notably, four of them are from low-income countries in Africa demonstrating the high relevance of these units in the context of food security. Finally, more than one third of the tools covered by the survey would allow for an economic assessment of farm operations but only few tools do actually estimate GHG emissions relative to economic gains although efforts to reduce agricultural GHG emissions can be associated with considerable costs or savings (MacLeod et al., 2015; Pérez Domínguez et al., 2016). Moreover, (financial) rewards were frequently mentioned as purpose for GHG accounting and high costs were identified as one of the main barriers for implementing emission reduction measures.

Rather than assessing an emission profile of a whole farm, farm-level GHG accounting is often used to assess climate footprints of different food items. When assessing only certain activities e.g., the production of a specific product, a respective allocation of overall farm-emissions is needed. In some cases, an allocation is complicated by the joint production of different outputs from the same activity branch (Rajagopal et al., 2017) such as e.g. milk and meat from dairy production (Flysjö et al., 2012; Ineichen et al., 2022; Zehetmeier et al., 2012) or the successive production of different crops in a rotation on the same unit of land (Costa et al., 2020; Goglio et al., 2016). Despite the complexity, emission allocation to different farm activities and/or emission sources and finally to individual products is widespread amongst the analysed farm GHG accounting tools. Allocation to different emission sources is more common than allocation to different products, which is more complex. Experience from practice show that allocation methods are ambiguous and differ considerably amongst different accounting tools (e.g. Ineichen et al., 2022; Thomassen et al., 2008). These findings are confirmed by Sykes et al. (2017), who found that decisions made at allocation stage have been shown to significantly affect results. The fact that users are not always aware of the underlying mechanisms of emission allocation highlights thus yet another source of ambiguity in farm-level GHG accounting.

4.4. Benchmarking systems and compensation and reward mechanisms

The survey shows that more than half of the tools cannot automatically distinguish between the influence of internal managerial decisions and external factors that are not under the control of the farmers. Almost all tools that can reveal such a distinction are of higher complexity, i.e., apply a Tier 2 or often a Tier 3 approach. But even then, a thorough assessment of the potential impact of a mitigation measure might only be possible in an ex-ante scenario analysis, where the effect of a change in management can be analysed independent of other confounding influences. According to the survey results, ex-ante modelling of mitigation measures and strategies seems to be a common utilization of the tools, and many projects and tools provide support for the identification and quantification of mitigation options. However, it is important to bear in mind that actual development can deviate from the ex-ante predicted impact. This restricts the use of ex-ante analysis for result-based compensation mechanisms.

Both for ex-ante and ex-post assessments of GHG emissions measures, benchmarking is an important practice (e.g., Renouf et al., 2018). Generally, three types of benchmarking systems can be distinguished which are all covered by the survey projects: “Best practice” which would mean the comparison to an ideal farm management, “Comparison among peers” and “Temporal benchmark system”, i.e., observing the development of a single farm or set of farms over time. However, as we have seen, the complexity and the different nature of explaining variables for different emission profiles is a substantial challenge. Varying benchmarks for different farm types and/or production systems have been proposed to address at least part of the problems (e.g., Hagemann et al., 2011; Lorenz et al., 2019; Stetter et al., 2022). The fact, that several projects are deploying a benchmarking system based on “national / regional averages subdivided by farm-type / production system” is suggesting that practitioners are aware of the fairness issues when comparing farms with diverging preconditions. On the other hand, about one third of the projects does not apply an explicit benchmarking system. Reasons for this are unclear but due to fairness issues project developers may opt to evaluate farm performance case by case, even though this means a much larger effort. In fact, projects without benchmarking systems analysed generally less farms (10 to <500) whereas the five projects with more than 500 farms all had some sort of benchmarking system in place.

Benchmarking can be one of the foundations of a reward or compensation mechanism. However, adjustments to the compensations may be necessary due to uncertainties, possible non-permanence of achievements and/or due to reservations in respect to additionality. This is particularly relevant for payments related to carbon stock changes (Ogle et al., 2023; Oldfield et al., 2022; Paul et al., 2023). In our survey only five projects implemented reward mechanisms, either based on absolute emissions, emission intensity or applied measures. Survey results suggest that in the majority of the projects there is an awareness of the challenges mentioned above. Project leaders seem thus to be reluctant to fully install (financial) reward or compensation mechanisms. The few projects that apply compensation mechanisms, use at least a Tier 2 model and adjustments for uncertainty, additionality and/or non-permanence of sinks are made. This confirms that fair compensation requires detailed methodologies and a thorough framework. These findings are also supported by the fact that there seems to be an equal reluctance to communicate the results of the farm assessments, be it via labels, exact numbers on product packaging or via advertisement within a general marketing strategy. In a survey conducted by Buma et al. (2024), experts suggested that some pathways of nature-based climate solutions, many with carbon credit eligibility and market activity, remain uncertain in terms of their climate mitigation efficacy. They recommend focusing on resolving those uncertainties before broadly scaling implementation of those pathways in quantitative emission or sequestration mitigation plans. If appropriate, those pathways should be supported for their co-benefits, such as biodiversity and food security.

4.5. Estimated and achieved emission reductions and corresponding challenges

GHG emission reduction potentials can be estimated considering only technical feasibility often termed “maximum technically feasible reduction” or “best available technology” (Loyon et al., 2016; here called “estimated theoretical”). These potentials differ from reduction potentials that additionally consider implementation constraints such as costs and non-monetary constraints (e.g. Arndt et al., 2022; Lengers et al., 2013; Roe et al., 2021; here called “estimated practical”). As illustrated by Buma et al. (2024), there is very high variability in the mean estimated mitigation potential of nature-based climate solutions between different experts and different studies. They suggest that a probable cause of this wide range was different constraints on the estimated potential, with some studies focusing on potential maximum impact and others on more constrained realizable impacts. Survey results confirm the importance to distinguish between the different levels of reduction potentials. Estimates of the theoretical potential were almost always higher than estimates of the practical potential. In addition, for a considerable share of the projects the estimated practical potential was not met by the effective reduction achieved ex-post in practice, demonstrating that even thoroughly assessed ex-ante reduction estimates may be overly optimistic. It may be hypothesised that with growing experience, people get more cautious in respect to the achievable reduction potentials in practice. However, besides the fact that more than 70 % of the survey respondents have more than 5 years of experience, we did not find any indication in this direction from our dataset, nor did we find that more experienced respondents were more reluctant in providing a specific answer on mitigation potentials. Yet, about one fourth of the respondents skipped the questions on the estimated or achieved emission reductions, commenting that the potentials are unknown, or the respective analysis are (still) incomplete. Some did comment that general assessments are not possible, partially because reduction potentials depend on the context and are highly variable across different farms.

Overall, we conclude that assessing realistic ex-ante or ex-post GHG mitigation potentials is a major challenge. The respective limitations are of great importance in an overall policy context. Without further knowledge and experience decision makers may draw wrong conclusions based on limited information. More experience in farm-level GHG accounting and better communication by experts would improve transparency.

4.6. Challenges, barriers and priorities for further development

Survey results show that using accounting tools is time consuming, highly complex and user friendliness is often unsatisfactory. Reservations with regard to data quality were mentioned as additional constraints. Comments suggested that particularly farmers struggle with these issues, especially when they are not yet familiar with the subject at hand. These findings align with the fact, that in most projects the tools are used by experienced professionals with a strong background and higher education in natural sciences and/or agronomy. However, we found no correlation between the length of practical experience and the number and type of problems encountered, suggesting that experienced users struggle with the same problems. High complexity, time exposure and issues of data quality were also highlighted as important limitations by other authors (e.g., del Prado et al., 2013; Hillier et al., 2016; Nemecek et al., 2024). Renouf et al. (2018) identified the balance between analysis capacity with ease of use as one of the key challenges.

Not only identification but also implementation of mitigation measures is hampered by a multitude of constraints, many of which are related to costs. Thereby, lack of funds for investments in facilities and/or technologies is only one aspect. Feedback from the survey suggests that “hidden” costs and non-monetary constraints are of great importance. In this line, e.g. Kreft et al. (2023) report on the importance of social and personal characteristics of farmers in the context of climate mitigation. Further insights from this perspective would be important to promote GHG reductions in agriculture (Moran et al., 2013).

Suggestions for next steps to promote the use of farm-level GHG accounting tools and boost GHG reduction were consistent with the constraints identified by the survey participants. Many proposals were in the direction of better access to more user-friendly, less complex and less time-consuming tools. However, as we have seen, this would most likely impair the accuracy and relevance of the results. A more practical way forward could thus be the better integration with existing databases (e.g., farm data for administrative use) and GIS and remote sensing systems. About 50 % of the tools covered by the survey do not yet use these techniques. Finally, standardized protocols and guidelines are also seen as a possible way forward. However, there are already many protocols and standards available since years (see non-exhaustive list in the supplementary material) and it is unclear, whether more of these guidelines will result in a better harmonization and less fragmentation.

On a more general level, survey participants were asked for promising options to promote climate friendly agriculture in practice. Responses suggest that there is still a general lack awareness and know-how. Accordingly, capacity building and consulting, often combined with the promotion of farm extension services, was frequently mentioned. Likewise, the promotion of demo-farms may be a promising strategy, combining aspects of awareness-raising, motivation and capacity-building. Together with many of our other findings, this suggests that currently further investments should rather focus on people and their expertise rather than on tools and technologies. This should be accompanied by consistent and integrated policies and regulations along the whole food chain, or in other words the promotion of an enabling environment, as mentioned in several comments in the survey.

4.7. Alternative mitigation approaches and need for an integrative system perspective

As we have demonstrated, establishing an accurate, comprehensive and fair MRV-system via farm-level GHG accounting tools is challenging and associated with high expenditures not only on a technical but also on a regulatory and administrative level. In highly developed production systems of high-income countries accurately assessing additional progress in production efficiency that is often small and uncertain is even more costly (e.g. Lewis et al., 2013). Our results demonstrate that the estimated associated reductions in GHG emissions, which are in the range of 10–20 %, are insufficient to meet necessary climate targets (Costa et al., 2022; Rosa and Gabrielli, 2023). In contrast in low- and middle-income countries there are considerable potentials for efficiency gains and closing the yield gap, thereby reducing the GHG intensity of agricultural production. However, these mitigation potentials are usually simple to assess without the need of sophisticated models. All these reflections raise the question whether the considerable costs of farm-level GHG accounting are justified by the insights gained and the induced emissions reductions.

Opportunities and limitations of the farm-level approach should thus be compared to other options. Various authors make the case for a rather systemic approach of agricultural GHG mitigation rather than focussing on the level of individual farm (Costa et al., 2022; Frank et al., 2018; Rosa and Gabrielli, 2023; Rosenzweig et al., 2020). In this context, system approach means specifically, extending the perspective and integrating all stakeholders along the food-chain, i.e., from producers to consumers. Whitfield et al. (2018) emphasize that only broad systemic perspectives position us to engage with the grand challenges of providing healthy diets for a growing population, avoiding unsustainable land-use change, and adapting to and mitigating climate change. Along this line, Rosa and Gabrielli (2023) conclude that the urgency of the climate crisis requires a paradigm shift towards net-zero or even net-negative emissions. Such targets are more achievable and logical at a sector-level rather than a farm-level (e.g., McNicol et al., 2024). Also, Springmann and Freund (2022) argue that compared to other environmental impacts, GHG emissions are less modifiable by farm-level management and more by changes in the mix of production, emphasising thus the system perspective and the role of the consumers. Measures and instruments for GHG mitigation in this direction have been explored by various authors. Promising approaches may be: (i) communication and awareness raising (e.g. Faccioli et al., 2022; Kim and Neff, 2009; van Dooren et al., 2017), (ii) true-cost accounting approaches (Nature Food, 2020), (iii) taxes and levies (Faccioli et al., 2022; Frank et al., 2017), (iv) changing subsidy systems (OECD, 2022; Springmann and Freund, 2022), (v) circular food systems (Billen et al., 2021; Frehner et al., 2022; Van Selm et al., 2022), (vi) or economic degrowth (Bodirsky et al., 2022; McGreevy et al., 2022).

4.8. Limitations of the study

Farm-level GHG accounting is a very dynamic field. Due to societal and governmental expectations and pressure the respective developments are both fast (with many initiatives underway) and furious (presenting a confusing and fragmented landscape) (Deconinck et al., 2023). Therefore, it is both likely and inevitable that this survey does not cover the most recent projects and/or that many projects restrained from completing the survey due to the lack of consolidated results. Additionally, data collected may be biased by motivational bias and self-selection bias (Bojke et al., 2021; El Benni et al., 2023). More interested, dedicated and more successful persons may be more willing to participate in a survey. This would possibly lead to an overestimation of the positive aspects and a softening of the challenges and difficulties.

A further limitation of our study may be that the survey does not cover a geographically representative sample. However, the indicated country in the survey may often refer to the origin of the expert that completed the survey and his/her institution. Thus, it is possible that the practical experience of the respondents covers a much wider geographical range. Still, the low participation from low- and middle-income countries may indicate that the call did not reach the respective target audience. Yet, the use of GHG accounting tools in these world regions may be not as widespread as in high-income countries. Besides lack of resources and technical skills, one reason for this may be that there is still much opportunity for efficiency gains that do not require highly sophisticated modelling approaches for impact assessment. Future research could analyse whether the design and the use of farm-level accounting tools differs between world regions.

The professional backgrounds and positions of the respondents and the connection of many of the surveyed projects to research programs may indicate that the call for the survey has been too narrowly focused on the research community. On the other hand, there were vast opportunities for addressees to disseminate the call and motivate further colleagues to participate. Therefore, the bias towards more research-based initiatives may be a consequence of the complexity of farm level GHG accounting. Non-academic users, namely the farmer community and the food industry may still depend on support from scientific institutions. Finally, the frequent connection to governmental initiatives and national or regional low-emission strategies suggests that agricultural GHG accounting is mainly promoted by public institutions. The focus of climate protection has only recently begun to shift from public institutions to the private sector, particularly in the food industry. Stakeholders of the private industry may thus be reluctant to disclose their (preliminary) data and experience in order not to lose competitive advantage or risk criticism of greenwashing. This may explain the low participation of projects from the private sector although it is known that various major retailers and other supply chain actors started own projects or are involved in GHG accounting initiatives (Deconinck et al., 2023).

5. Conclusions and recommendations

The relatively small sample size of 30 projects with 23 different tools covered by the survey may be considered as limitation. We therefore base our conclusions and recommendations on conceptual and holistic inferences derived from the whole body of evidence, i.e., both from our literature review and the survey results. In doing so, we strive to provide comprehensive support based on both the latest academic knowledge and the evaluated practical experience. Furthermore, we emphasize that our conclusions apply primarily to comprehensive assessments of entire agricultural holdings with all associated activities and not necessarily for individual specific activities such as e.g., feed supplementation or on-farm energy use.

The development of tools for GHG accounting on the farm level can help to lever the potential of GHG mitigation. Even, the parallel development of different tools for different projects, regions and purposes can be a helpful step towards more climate-friendly production systems. However, before starting a farm-level GHG assessment the overall purpose and in particular the nature and design of the intended mitigation measures should be considered carefully. This should lead to an informed decision on which tool to use and determine the way results are interpreted in a specific context. The design and complexity of the tool used should balance costs and benefits of GHG accounting.

On a technical level GHG emission accounting is already quite advanced. However, survey results demonstrate, that many tools do not automatically provide ready-to-use indicators for important and delicate aspects such as e.g. uncertainties, data quality, leakage and issues related to emission allocation, system boundaries and system interactions beyond the farm gate. Accordingly, a thorough interpretation of the results requires additional reflections and above all great experience. This suggests that most tools are not ready for autonomous use by e.g. farmers or companies of the food industry. Farm-level GHG accounting should thus always be performed in a consultancy context with professional and experienced experts.

Detailed methods are essential for accurate assessments, for distinguishing between different influencing factors that are or are not under the control of the farmers and for establishing a fair benchmarking system and compensation mechanism. Additionally, accurate emission allocation to different activity branches or products requires more sophisticated models. Altogether, the complexity of the subject makes thus farm-level GHG accounting time consuming, costly and difficult to communicate. We consider it rather unlikely that further methodological improvements of tools alone will significantly lower uncertainties and workload and improve practicability.

The great diversity of methodologies of farm level GHG assessment tools lead to a great heterogeneity of results, making them difficult to compare. Results should always be interpreted considering the respective system boundaries, possible leakage and possible consequential interactions with the whole agri-food system. The later comprises particularly the land-use competition for food, feed and other uses. Additionally, soil carbon changes should always be reported separately from other farm GHG emissions due to their high uncertainties and issues with saturation and permanence.

Informed decision making should never rely on a single reporting unit. It should rather be based on a set of evaluation criteria. These should include absolute as well as relative metrics and be in line with the overall societal and political goals. Regarding GHG footprints of food items it is important that users understand the respective emission allocation approaches of the tools and their effects on results.

An evaluation of a farm's efforts for climate mitigation is basically only possible in an ex-ante assessment. The alternative, i.e. a continuous tracking of a farm's development over time by repeated assessments, would be extremely resource intensive and restricted by fairness considerations. Due to the intricacy of the subject matter, we thus conclude that communication of self-induced achievements in GHG mitigation is delicate and prone to misinterpretation. Likewise, fair result-based benchmarking systems and compensation mechanisms are difficult to implement and - although possibly less effective – measure-based or hybrid models might be preferable alternatives. In accordance with this, we consider that the relevance of current farm-level GHG accounting tools to the business of unconstrained carbon markets is limited.

Because theoretical, practical and actually achieved emission reductions differ significantly, any carbon offset claims that are based on ex-ante evaluations should be followed by a verification of the attained impact. We consider that without a clear declaration of the underlying assumptions, particularly concerning implementation barriers and applied system boundaries, ex-ante assessments remain dubious, if not misleading and possibly overly optimistic.

Overall, we conclude that farm-level GHG accounting tools provide useful information for climate protection if carried out with appropriate care and interpreted by experienced experts. The highest possible level of transparency should be ensured at all times in all aspects. Moreover, the matter of agricultural GHG accounting is overly complex and most of the limitations of the tools may be difficult to overcome by developing more detailed and comprehensive methodologies. We thus suggest that besides further development of tools, priority should be given to capacity building for use of tools and thorough interpretation of the results. Even though a carpenter certainly needs a good hammer, it is above all experience that enables him to hammer a nail straight in.

Finally, our results show that estimated and achieved emission reductions at the farm level on its own are not sufficient to reach the emission reductions needed to achieve the 1.5° or 2° goal. These efforts must therefore be complemented by bold actions at the level of the food system, particularly addressing the demand side.

CRediT authorship contribution statement

Daniel Bretscher: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Nina Grassnick:** Writing – original draft, Conceptualization. **Collier Isaacs:** Writing – review & editing, Data curation. **Claudia Heidecke:** Writing – review & editing. **Bettina Koster:** Data curation. **Lutz Merbold:** Writing – review & editing. **Jens Leifeld:** Writing – review & editing.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180688.

Data availability

The data that has been used is confidential.

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