frontiers | Frontiers in Climate

TYPE Original Research
PUBLISHED 22 September 2025
DOI 10.3389/fclim.2025.1627432

OPEN ACCESS

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RECEIVED 12 May 2025
ACCEPTED 31 July 2025
PUBLISHED 22 September 2025
CORRECTED 30 September 2025

CITATION
El Zohbi J, Griesing L, Torma G and Rechid D (2025) What regional agricultural actors want to know about carbon dioxide removal in Northern Germany. *Front. Clim.* 7:1627432. doi: 10.3389/fclim.2025.1627432

What regional agricultural actors want to know about carbon dioxide removal in Northern Germany

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Many countries, including Germany, have made their climate targets dependent on the implementation of methods for removing carbon dioxide from the atmosphere. Actors in the agricultural sector can contribute to this implementation. However, there is a knowledge gap regarding carbon dioxide removal (CDR) among agricultural actors. In this study, we interviewed 34 agricultural actors at the micro, meso, and macro levels to identify the factors hindering the implementation of CDR practices, namely soil carbon sequestration, biochar, and agroforestry. We identified 22 information needs related to the dimensions of Climate change mitigation, Technological conditions, Environmental impacts, Economics, Policy & government, and Social aspects from the interviews. Farmers expressed more information needs compared with representatives from farming associations or local and regional administrations. Across all interviews, recommendations for action were most requested, with a high preference for information in digital online formats. Our findings provide a checklist for future research in the form of co-developed actionable knowledge between researchers and agricultural actors to increase the knowledge but especially the use of agricultural practices to remove carbon dioxide from the atmosphere.

KEYWORDS

agriculture, carbon-dioxide removal, soil carbon sequestration, biochar, agroforestry, knowledge creation

1 Introduction

In addition to reducing carbon dioxide (CO_2) emissions, removing CO_2 from the atmosphere, termed carbon dioxide removal (CDR) (Smith et al., 2023), is essential to achieve net-zero emissions (IPCC, 2022). This means that the CO_2 released into the atmosphere due to anthropogenic activities should be actively removed from the atmosphere and locked away.

CDR efforts on the ground involve deploying new technologies such as direct air capture and carbon storage (DACCS); however, owing to their limitations such as high energy demand, high cost, and extensive infrastructure requirements, they cannot be operated on a large scale yet. Meanwhile, already established practices, particularly those in forest management and agriculture, are considered effective CDR methods, as they are regarded as mature technologies. These CDR efforts rely on changes in practices and choices implemented at the individual level by single decision makers, such as farmers (Singh et al., 2018; Buck and Palumbo-Compton, 2022; Barbato and Strong, 2023; Otto and Matzner, 2024).

Among the prominent CDR practices applied by farmers are soil carbon sequestration, biochar application, and agroforestry. Farmers can contribute to the removal of additional CO_2 from the atmosphere by practicing effective management strategies on their land that change the balance between carbon inputs and losses (Mattila et al., 2022). The concept underlying

this practice is that plants facilitate CO_2 removal from the atmosphere by storing carbon in their biomass first and then possibly transferring it to the soil in the long term. The latter process known as soil carbon sequestration can increase the equilibrium level of soil organic carbon content (Don et al., 2024). Soil carbon sequestration comprises a series of practices, including planting in periods when plants are generally not cultivated (Poeplau and Don, 2015). Some studies refer to these practices as regenerative agriculture (Khangura et al., 2023); however this term remains controversial (Daverkosen et al., 2022). Recently, adding biochar to agricultural fields has emerged as a novel method for soil carbon sequestration (Schmidt et al., 2021). Biochar is produced when biomass is burned in the presence of very little oxygen. When added to soil, it can store carbon for long periods of time and enhance soil fertility (Hagemann et al., 2017). Another CDR method is converting a field into an agroforestry system (Smith et al., 2024). Agroforestry is the practice of deliberately integrating woody vegetation such as trees and shrubs with crop and/or pasture or livestock (Quandt et al., 2023). Agroforestry systems can sequester and store atmospheric CO_2 in plant parts and soil over long periods, as trees and shrubs are perennial plants (Schroeder, 1994; De Stefano and Jacobson, 2018).

The conventional method of generating and disseminating research results and uniform solutions does not sufficiently improve the implementation of CDR-related practices (Kirchhoff et al., 2013; Šūmane et al., 2018; Shrum et al., 2020; Hurley et al., 2022; Nordström Källström et al., 2024). Transdisciplinary approaches can produce actionable knowledge; however, actionable knowledge that is required for implementing CDR-related practices is still lacking (Zelikova, 2020). In the present study, we investigated the support required for agricultural actors to enhance the implementation of CDR-related practices. We aimed to identify the information needs that would enable intensive collaboration between researchers and agricultural actors to support the implementation of CDR-related practices in the future.

We decided to carry out our study in Northern German in one federal state (Schleswig-Holstein) and the neighboring city state (Hamburg). The region covers an area of 16,555 km^2 and is therefore almost as large as Kuwait. Almost two-thirds of the area is used for agriculture (Kowalewski and Schulze, 2010). In this region, most farms are organized as independent small family-owned businesses, meaning that the farmers decide on investments and farm organization (Statistikamt Nord, 2024). This is an important aspect in answering the question of what is required for the implementation of CDR practices in the agricultural sector. One advantage of selecting this region for our study was that the region has already been well studied in research projects about Germany's Agricultural Knowledge and Innovation System (Birke et al., 2021; Bae et al., 2024). It is considered a key concept in identifying, analyzing, and assessing the various actors in the agricultural sector as well as their communication and interaction for innovation processes (Knierim et al., 2015).

We conducted 29 interviews among agricultural sector actors in Northern Germany, including farmers, farmers' associations, and representatives of agricultural governance structures. Our study addressed three main questions:

1 How familiar are agricultural actors with the concept of CDR?
2 Which agricultural actors need to know what?
3 Which formats are considered best for implementing research findings into practice?

The analysis of the interviews was guided by these questions, which allowed us to address the information gap by uncovering the specific, regional information needs of agricultural actors in relation to CDR practices and compiling their ideas on how they would like to receive the information.

2 Materials and methods

We started our study with a stakeholder mapping of the agriculture sector in Northern Germany. Through this mapping, we intended to identify representative interview partners who could be considered for the implementation of CDR practices in the agricultural sector. The first step was to define relevant stakeholder categories (Durham et al., 2014). When defining the categories, we oriented ourselves with the areas of activity in the agricultural sector, e.g., agricultural chamber, farmer, farmers' association and union, adviser and non-governmental organization. A key starting point for the categories, was inventory process in relation to the Agricultural Knowledge and Innovation System in Germany (Birke et al., 2021; Bae et al., 2024). The two reports provided the institutional landscape of our study region, where the agricultural actors operate. With the categories, we collected region-specific contacts for each group relevant through internet research and visiting agricultural events in the region. It was important for us to collect actors from the locals, e.g., farmers, and the regional level, e.g., federal state administration. Stakeholders' contacts included farmers with and without CDR experience, farmers' organizations, biochar producers, non-governmental organizations, regional networks, and representatives of both local and regional administrations and authorities in Northern Germany. The contact list was expanded using snowball sampling—each interviewee was asked for contacts they thought were important for inclusion in our study. In total, 120 contacts were identified.

2.1 Selection process

Researchers investigating the social acceptance of new technologies often take a socio-systemic approach (Wüstenhagen, et al., 2007; Ellis et al., 2023; Torma and Aschemann-Witzel, 2024) based on processes that operate at three levels. In the present study, we interpreted these three levels as follows: (1) micro level: the smallest unit of analysis that represents the individual perspective, (2) meso level: includes various informal social group affiliations as well as formal associations and networks, and (3) macro level: the highest level of analysis, encompassing political structures and governance processes.

To identify representative interview partners for the implementation of agricultural CDR-related practices in Northern Germany, we utilized the above concept to divide our 120 contacts into these three levels (Figure 1). All farmers with or without CDR experience (soil carbon sequestration, biochar, and agroforestry) were assigned to the micro level. Farmers' associations, agricultural advisors, biochar producers, environmental associations, non-governmental organizations, and regional networks were assigned to the meso level. The macro level included representatives of local or regional authorities involved in agricultural issues. For the micro level, we sent invitations

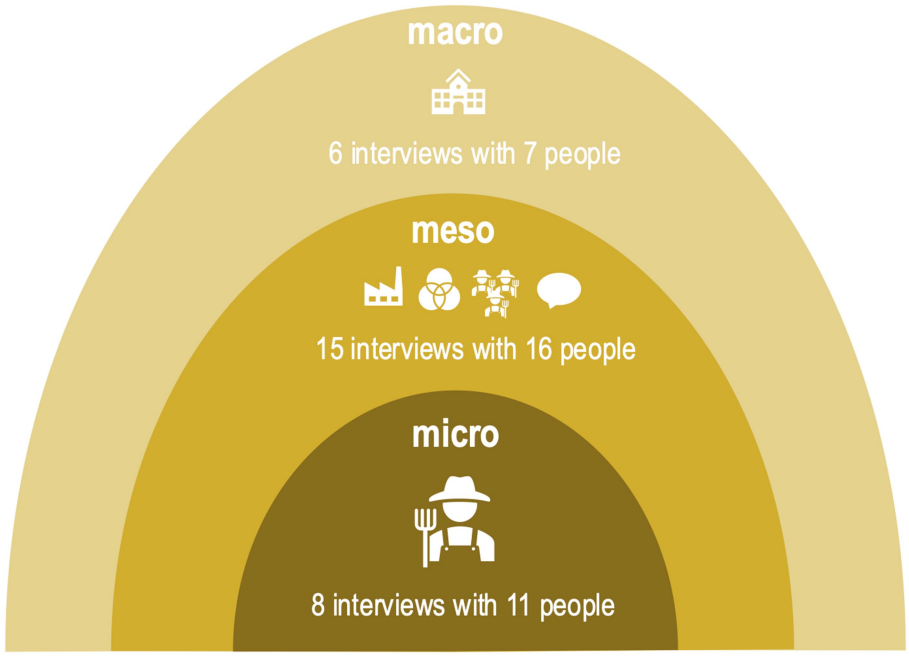

FIGURE 1
Distribution of interviewees at the micro (farmers including four farmers with strong CDR experience), meso (farmers associations, agricultural consultants, biochar producers, non-governmental organizations, and regional networks), and macro levels (representatives of regional and local authorities).

by email to all the farmer contacts we selected. For the meso level, we prioritized those who we assumed might have an interest in CDR. For the macro level, we contacted all representatives who worked wholly or partly in the agricultural sector and might have had CDR on their agenda.

In total, we sent 63 initiations via email for the interviews. The response rate with interview confirmation was 46%. We continued sending invitations until few or no new insights appeared to be generated and concluded that theoretical saturation had been reached at 29 interviews.

All the interviewees signed an informed consent form before appearing for the interviews. The consent form contained information regarding the study aim, project, content, and data protection rights and assured anonymity. The interviewees did not receive any compensation.

2.2 Data collection

We conducted 29 interviews with 34 participants between January and July 2023. The interviews typically lasted about an hour, but when more than two people participated, the interview duration was extended to 1.5 h. All interviews were conducted online, with the exception of four on-site interviews. The interview language was German.

If the interviewees agreed, the interviews were recorded and later transcribed. Three interviews were not recorded owing lack of permission, but we ensured that the researchers who conducted the interview took notes.

The interview guide was adapted according to the interviewees' work profile and relation to CDR, knowledge and experience in general and specific CDR practices, evaluation of CDR methods, and informational and knowledge needs. Following feedback from three test interviews, the questions were revised to improve the clarity of the phrasing. The interview guide is presented in Appendix A.

Each interview was assigned an identifier for the analysis. The numbering corresponds to the order in which the interview was conducted. Each identification number was assigned a corresponding level. For example, an interview with a farmer from the meso level was coded #1_meso.

2.3 Data analysis

We conducted a qualitative content analysis of the transcribed interview data (Schreier, 2012; Mayring, 2014). The core of the analysis was to assign successive parts of the qualitative data to categories of a coding scheme. We built a coding frame for each of the three levels (micro, meso, and macro). The coding was then extended to single CDR practices: soil carbon sequestration, biochar application, and agroforestry. The coding scheme also captured when and how participants first heard about CDR and how they would like to receive missing information (see Appendix B).

To ensure that we captured knowledge needs holistically, we used the six descriptive dimensions of the CDRterra assessment framework (Havermann et al., 2024) as an analytical framework. Each dimension was described using a guiding question (Figure 2). We used these guiding questions (Havermann et al., 2024) as inspiration sources to identify knowledge needs in our qualitative data. To facilitate the use of our findings in future transcapillary dialogues (Kirchhoff et al.,

Identifier	CDR type	Dimensions including guiding question and information needs
		Climate change mitigation *What are the effects of CDR on greenhouse gas emissions and overall climate change?*
Q1	Biochar	How long does biochar store CO_2?
Q2	Non-specific CDR	What are the synergy effects produced when several CDR-based practices are implemented together?
Q3	Non-specific CDR	What standardized data collection is in place for measuring and evaluating CO_2 and other greenhouse gases relevant to agriculture?
Q4	Non-specific CDR	Which CDR-based practices in agriculture store CO_2 for the longest duration?
		Technological conditions *Are suitable technologies, resources, and infrastructure available? Which characteristics influence upscaling?*
Q5	Soil carbon sequestration	How can the humus content be significantly increased in the long term?
Q6	Biochar	What is the best source of biomass to produce biochar?
Q7	Non-specific CDR	How easy (or costly) is it to integrate a CDR practice into a farm's existing production structure?
Q8	Non-specific CDR	Are all necessary technical innovations available for the application of CDR-based practices in agriculture?
		Environmental impacts What are the impacts of CDR on the natural world?
Q9	Soil carbon sequestration	How does humus affect the exchange capacity of nutrients for plants?
Q10	Biochar	What exactly occurs in the soil after biochar is added?
Q11	Biochar	Does biochar introduce harmful substances into the soil?
Q12	Non-specific CDR	Which CDR practices can farmers use to achieve the most positive ecological co-benefits?
		Economics What are the economic costs, barriers, and benefits of CDR methods?
Q13	Biochar	How can the use of biochar become economically efficient for farms?
Q14	Non-specific CDR	What kind of competitive advantage can farmers gain by using CDR practices?
Q15	Non-specific CDR	How do the yields change when applying CDR practices?
Q16	Non-specific CDR	How can it be ensured that the use of CDR practices is economically beneficial for farmers?
		Policy & government How mature is the level of policy and governance for achieving the level of CDR deployment?
Q17	Biochar	What incentives can be introduced for the use of biochar?
Q18	Non-specific CDR	How can long-term, political, science-based framework conditions be established to provide farmers with planning security?
Q19	Non-specific CDR	How can regulations that reasonably combine existing regulations with CDR be established?
		Social aspects How is the public perception towards CDR? How does CDR interact with justice principles?
Q20	Soil carbon sequestration	How can farmers who have already sequestered a lot of carbon in the soil be remunerated?
Q21	Non-specific CDR	How can farmers be rewarded for the provision of public goods by CDR practices that provide public welfare services?
Q22	Non-specific CDR	How does the local community react to the use of CDR practices?

FIGURE 2
Information (Q1-Q22) assigned to the six dimensions. The content of each dimension is characterized by a guiding question.

2013) and co-development processes (Hewitt et al., 2020), we documented the interviewees' knowledge needs as information needs.

For quality reasons, we coded the qualitative content analysis in a two-phase step. One author (GL) started the coding process, and a second author (JEZ) critically assessed the coding and revised it. The analysis of the interview data was flexible and dynamic, owing to its qualitative nature (Schreier, 2012; Torma and Aschemann-Witzel, 2024). MaxQDA and Microsoft Excel were used for the analysis.

3 Results

The results of the qualitative analysis are structured according to the three questions of our study.

3.1 How familiar are agricultural actors with CDR?

At the beginning of each interview, we introduced our project and the scientific definition of CDR to the interviewees. During the interviews, it became clear that some interviewees had an incomplete understanding of CDR. This misconception regarding CDR emerged mainly among interviewees at the meso and micro levels. For example, some interviewees assumed that they were already active in CO_2 removal but listed methods that only lead to the reduction of CO_2 or other greenhouse gas emissions:

> *"I worked in a large animal feed company. Six years ago, the emissions balance didn't play a role, but later around 2020, we started looking at it, for example, how to reduce methane emissions with linseed." #24_micro*

We asked all interviewees whether they had heard of CDR before the interview and whether they could remember when they first came across the topic. All participants were familiar with CDR-related practices; however, only 18 of the 29 respondents were familiar with the actual concept of CDR. The earliest year an interviewee reported having heard of the concept of CDR was 2013. We observed that most interviewees found out about CDR in 2018 and 2019. We also observed that practices for carbon sequestration in the soil and humus build-up have long been known in the agricultural sector. The actors were not concerned about the climatic aspect but only soil health; the effects on the climate system were rather new for some actors.

> *"But of course, carbon sequestration in the soil has always been an issue. Now there is this new term [CDR] that I didn't know before." #15_macro*

3.2 Which agricultural actors need to know what?

Although the interview guide was open to all possible land-based CDR methods, the discussion mainly focused on three CDR practices: soil carbon sequestration, agroforestry, and biochar application.

The interviewees highlighted the need for knowledge across all six dimensions: Climate change mitigation, Technological conditions, Environmental impacts, Economics, Policy & government, and Social aspects (Figure 2). A total of 22 information needs were identified, with each dimension encompassing 4 questions, except for the dimensions Policy & government and Social aspects, which had only 3 questions each. Most of the statements in the interviews led to information needs related to Economics, followed by Climate change mitigation and Policy & government (Figure 3). Questions regarding other dimensions were equally important for the interviewees.

We analyzed the relative frequency of the statements provided by the interviewees at the micro, meso, and macro levels that led to the 22 information needs (Figure 2). The analysis revealed that most of the questions were asked by farmers compared with interviewees from the meso and macro levels. Local and regional authorities articulated the least need for information. They were less concerned about single CDR practices but had more questions regarding CDR practices in general.

Farmers had questions regarding both specific and general CDR practices. Their interest was highest in the Economics dimension. Interestingly, farmers also showed a high interest in Social aspects, followed by Technological conditions. Actors at the meso level contributed equally to the information needs, showing the highest interest in the Economics dimension, followed by Climate change mitigation and Policy & government.

3.2.1 Climate change mitigation

This dimension explores the effects of CDR on CO_2 emissions, from the durability of the carbon storage to the quantification and verification of it. All four information needs (Figure 2, Q1–4) identified were of interest to actors at the meso level. Farmers contributed to three of the four questions, and only two questions were relevant to the macro level.

Some interviewees at the micro and meso level questioned the long-term mitigation potential of biochar (Q1).

> *"With biochar, I can determine exactly how much carbon is in it under the microscope, but of course these are only laboratory values. Because we haven't had this type of coal in the soil for 1000 years yet. What happens then?" #10_micro*

A question raised only by actors at the meso level concerned the combination of different CDR practices (Q2), e.g., the application of biochar with enhanced weathering, combining soil carbon sequestration with biochar, or methods we are not aware of yet.

> *"How do two CDR practices influence each other? I still find that exciting. Where are the synergies between the individual methods?" #1_meso*

The quantification of greenhouse gasses was of concern to the actors at all three levels (Q3). It involves the measurement of carbon in soils to correctly quantify the carbon content. This is a cause of concern because soils are heterogeneous, which means that a large number of soil samples are required for the quantification, which is not always done in praxis. Some interviewees mentioned that other agricultural greenhouse gasses such as methane and nitrous oxide would need to be measured at the same time to evaluate the effect of a CDR measure. Others expressed their concerns about greenwashing effects if measurements were not performed correctly and in a standardized manner.

> *"Many things are difficult to measure but it is a crucial point, because you have to make it tangible so that it can be implemented politically, so that someone will do it." #12_meso*

In general, actors at all levels wanted to know which CDR practices would ensure the longest storage time for CO_2 (Q4). Interviewees questioned whether biochar had the longest durability or if other compounds were more effective.

> *"What solutions do we have that will last for at least this century and then see what else is possible in 50 years' time?" #14_meso*

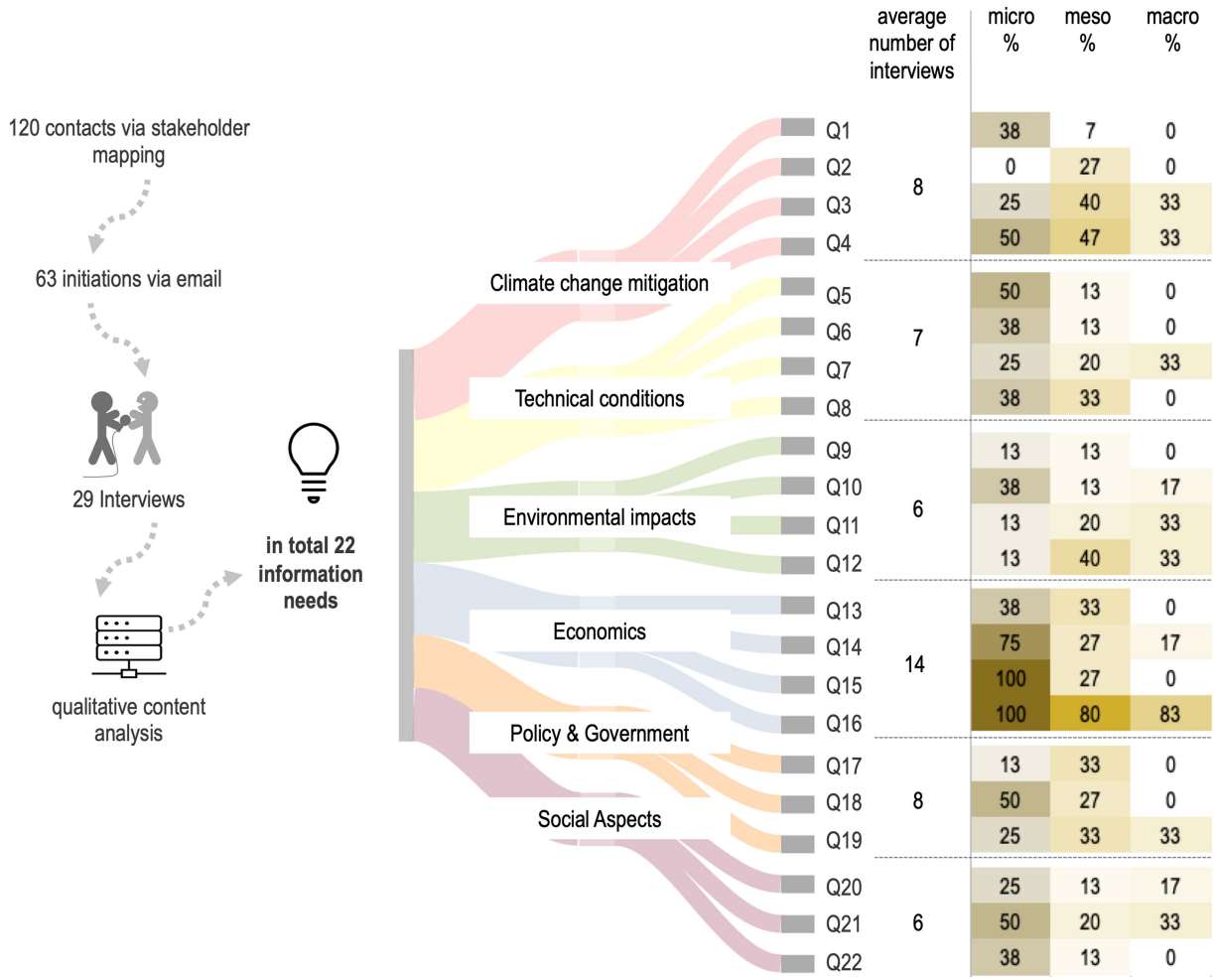

FIGURE 3
Overview of the data analysis process. Using qualitative content analysis, we identified a total of 22 information needs from six dimensions. The colored cells on the right-hand side show the relative proportion of interviews from micro, meso, and macro level that each information need was derived from. See Figure 2 for the information needs.

3.2.2 Technological conditions

This dimension is concerned with resource availability and infrastructure, as well as the need for upscaling CDR practices. The four identified questions (Figure 2, Q5–8) were derived from interviews with actors at the micro and meso levels; only one question was of interest at the macro scale.

Questions regarding soil carbon sequestration centered on how humus content can be increased under different starting conditions in soils. Additionally, once the carbon content in the soil is increased, what are the methods to ensure that it remains at that level. Some interviewees expressed doubts regarding wether this could be done so easily (Q5).

> *"Maintaining or even increasing the humus content in the soil would be a valuable contribution. Some people think they already know everything about it. You can challenge them with a few questions. There is an extreme need for research here." #13_meso*

The main question concerning biochar was regarding the biomass used to produce it (Q6). The interviewees conveyed that they would not appreciate it if the biomass was an imported product. Others were concerned about contaminated biomass, for example, using old railway ties, or that biomass is in competition with wood chips.

> *"The biomass should be regional. But will it be missing somewhere else?" #14_meso*

Some CDR practices can be more easily integrated into daily farm business than others. The shift from crop management to agroforestry has entailed a complete change in production. These changes affect several factors, including the plants that are grown, the machines used, and the number of laborers needed. These concerns were equally distributed among the three levels (Q7). IN addition, some practical questions were raised about its implementation. Some actors questioned when and how biochar or rock powder should be spread on large areas of the fields for enhanced weathering.

> *"The measures that really make a difference are such that they require a significant change in farming methods. But of course, I can understand the skepticism." (#5_macro)*

One interviewee mentioned that there might also be technologies that people are not yet aware of but that may be within farmers' reach in the future (Q8).

3.2.3 Environmental impacts

This dimension concerns the impacts of CDR methods on the natural environment. The four questions (Figure 2, Q9–12) were identified from the interviewees at all levels, except for one question that was based on contributions from the micro and meso levels only.

Regarding soil carbon sequestration, some interviewees from the micro and meso levels raised questions about the natural processes in the soil when the carbon content is increased (Q9). One interviewee expressed the following point:

> *"There still exist a few technical issues with humus, e.g., accumulation or exchange capacity of nutrients. How do they work exactly?" #4_meso*

Regarding biochar, the interviewees at all three levels wanted to know the effect of biochar on the soil and environment (Q10):

> *"If I have introduced biochar into the soil, what happens to the other factors around it? What else happens in the soil? I think there is absolutely a need for information. #10_micro*

A concern mentioned a few times by actors at the micro and meso levels was that biochar can release pollutants into the soil (Q11). Some interviewees revealed that this concern was also related to older trials and outdated scientific publications.

> *"Accumulation of harmful substances - this is an issue that still needs to be discussed. Well, it is being discussed, but we need more certainty and clarity in any case." #14_meso*

The most significant question on the environmental dimension was primarily posed by actors at the meso and macro levels—the co-benefits of CDR practices (Q12). Interviewees mentioned various advantages that could be appreciated, including ecological benefits, adaptation to climate change impacts, and a positive effect on water management. The interviewees wanted to know which CDR measures provided the greatest ecological benefits. Farmers that had already implemented CDR-related measures, such as agroforestry or regenerative agriculture, did so because they believed that these methods have multiple added benefits, particularly for the environment.

3.2.4 Economics

This dimension is dedicated to questions related to the costs and economical aspects of CDR. The four questions (Figure 2, Q13–16) identified were of significant interest to farmers, as well as actors at the meso level, albeit to a lesser extent. Interviewees at the macro level contributed to two questions.

Biochar is a relatively expensive product for farmers to use. Biochar producers discussed the technical scalability to reduce the price (Q13). Meanwhile, the need for farmers to be economical was also highlighted. If a fertilizer is cheaper than biochar and leads to a higher yield, then biochar will not be used.

> *"The use of biochar is very realistic for me if the price ratio is right. But how?" #18_meso*

Some discussions and information needs dealt with the fact that farmers could gain competitive advantage from implementing CDR (Q14). Some interviewees questioned whether it could improve the image of a farm and could be used for optimizing the direct marketing strategy of a farm. The interviewees mentioned the advantages and disadvantages of CO_2 certificates. In addition, the extent to which private-sector players should be involved was discussed.

One topic raised by all farmers was the effect of CDR practices on yield (Q15). Some farmers argued that agroforestry creates more biomass, in addition to increased photosynthesis, leading to higher yields. Other farmers expressed doubt. Another point raised was that the effect of each method depends on the farm conditions and environmental conditions. Some actors at the meso scale mentioned that they could not comprehend what carbon sequestration in the soils meant for plant growth. Farmers, on the other hand, hoped that biochar would have a positive effect on the yields.

> *"We buy the biochar; we spread it. And the yields must be higher because the costs of spreading must be covered." #28_micro*

The question about the cost-effectiveness of CDR practices was most frequently expressed by all interviewees (Q16). All farmers were concerned about this, and 80% of the interviewees from the meso and macro levels contributed to this question. Everyone agreed that the use of CDR must be profitable for farmers. While reference was often made to direct financial rewards and how farmers could be remunerated, the co-benefits of CDR for the public were also highlighted.

3.2.5 Policy and government

This dimension involves the political setting in which CDR options are implemented. The three identified questions (Figure 2, Q17–19) were derived from interviews with actors at the micro and meso scales. Only one of the three questions was of concern to the macro level actors.

The interviewees discussed the incentives, regulations, and political conditions that ensure the use of CDR practices. As biochar application is a novel CDR method, the interviewees discussed the incentives that should be created to encourage farmers to use biochar (Q17). Some drew a comparison with the introduction of solar panel systems because they were convinced that innovative technologies always require incentives.

> *"That's where I see the need for new incentive instruments to provide more support for agriculture to realize CDR in practice." #5_meso*

More than half the farmers and meso-level representatives complained that politicians were creating uncertainty and failing to provide planning security to farmers. Some interviewees believed that the political targets in the agricultural sector lacked scientific evidence. Some farmers feared that political and legal frameworks would prevent them in the future from changing the new management system to the previous one (Q18). These concerns can be interpreted through the lens of path dependency, as farmers and meso-level actors were apprehensive of being stuck with irreversible land-use decisions under uncertain political conditions. Additionally, agroforestry systems—especially tree planting—were perceived as creating long-term commitments that might restrict future management flexibility.

> *"This trust in government policy is very important. There is a real fear that something will ultimately be taken away from you in terms of profitability." #24_micro*

Interviewees at all levels reported that farmers must deal with many regulations. They feared that an increase in CDR policies would lead to more regulations. Other farmers reported that the existing policy interventions were not implemented because they were not suitable for practical use (Q19). Regarding CDR, the interviewees wished to not only incorporate it into existing regulations but also ensure that the measures did not contradict each other.

> *"There are many regulations that come from different directions and are not coordinated in a meaningful way. How can it be ensured that everything is interlinked and harmonized?" #11_meso*

3.2.6 Social aspects

This dimension relates to social implications such as the public perception of CDR, procedural and distributional justice, and human health and well-being. Three questions (Figure 2, Q20–22) came from interviews at all three levels, except for one in which the macro level had no contribution.

Some actors across all levels asked for equal rights when it came to incentivizing soil carbon sequestration. Interviewees expressed concern that farmers who have already accumulated a lot of carbon in their soils will have a less favorable opportunity to receive compensation than farmers who are only now starting to change their practices (Q20).

Overall, agriculture is essential for offering a wide range of public goods. In addition to biodiversity and landscape, agriculture can also help provide environmental benefits such as good air and water quality, soil health, and measures to tackle the effects of climate change. The deployment of some CDR practices inherently contributed to these public goods, and a question was raised about how to reward this (Q21). This question was raised by the regional authorities, as well as half of the farmers.

> *"There is a lot of talk about shifting from being a classical farmer to becoming a smart-climate farmer. And the question is, how do you reward that?" #27_macro*

Another question (Q22) raised by farmers and some actors at the meso scale deals with the perception and attitude of the local community toward the visual changes caused by some CDR practices. A farmer reported that when he collected biomass from hedges around his fields to produce biochar, the locals called the nature conservation office to complain about his action. Farmers planting shrubs and trees to build an agroforestry system have experienced negative attitudes from people in the neighborhood.

3.3 Which formats are considered best for implementing research findings into practice?

We asked the participants about the sources from where they usually obtained their information about climate change and climate mitigation. The media, including news, social media, and podcasts, was one such source. Some farmers mentioned agricultural journals as a source of information. Some actors at the meso and macro level had subscriptions to scientific-based newsletters. However, many actors expressed that they searched the Internet whenever they wanted to know something new.

We also asked the participants their preferred methods for compiling the research findings and missing information regarding CDR. Interestingly, farmers and some meso and macro level actors also stated that dealing with the latest scientific findings was beyond the scope of their daily responsibilities. However, all interviewees agreed that, regardless of the format, the information contained should have strong practical relevance, be presented in simple language, and be well visualized. In terms of formats, the interviewees mentioned that the traditional transfer of information from science to practice is often not feasible. All interviewees reported non-applicability of reports or brochures. Interviewees explained that they did not have sufficient time and often did not understand the scientific procedure.

> *"I don't want to get involved in research. A report is far too long, but what I need is the actual situation that is written in an understandable way for practitioners." #19_meso*

Actors at all levels expressed a clear need for scientific results in the form of recommendations for actions, guiding materials, or concepts (Figure 4). Farmers often mentioned that they wanted to know exactly how effective the CDR method was and what its advantages and disadvantages were (see section 3.2).

The authorities enact laws that are closely linked to the support measures and thus influence the practices of farmers. Therefore, one farmer expressed their wish to receive guidelines directly from the authorities:

> *"It would be best if there were a letter from the Ministry of Agriculture with a roadmap for society as a whole, describing various measures and setting out the direction of what we have to do." #3_micro*

Farmers also mentioned that for the procedure of developing guidelines to enhance the implementation of agriculture-based CDR, improving the communication between farmers and authorities would be recommended.

> *"We farmers always criticize the fact that the authorities always do a lot of learning by doing when it comes to new guidelines, even though this wouldn't be necessary if they would just listen to the farmers. As it is, they always have to painstakingly learn what they could have been told beforehand." #28_micro*

Actors at the meso-level also expressed a strong need for guidance.

> *"I need a ready-made concept that says you can do something here, you can intervene here, I can communicate this to the farmers." #19_meso*

One interviewee suggested creating guidance materials for biochar; researchers should first bring all market players together to jointly develop the most useful and practical information. Another interviewee of the meso-level noted that there was often a lack of ability to convert data and information into sustainable actions.

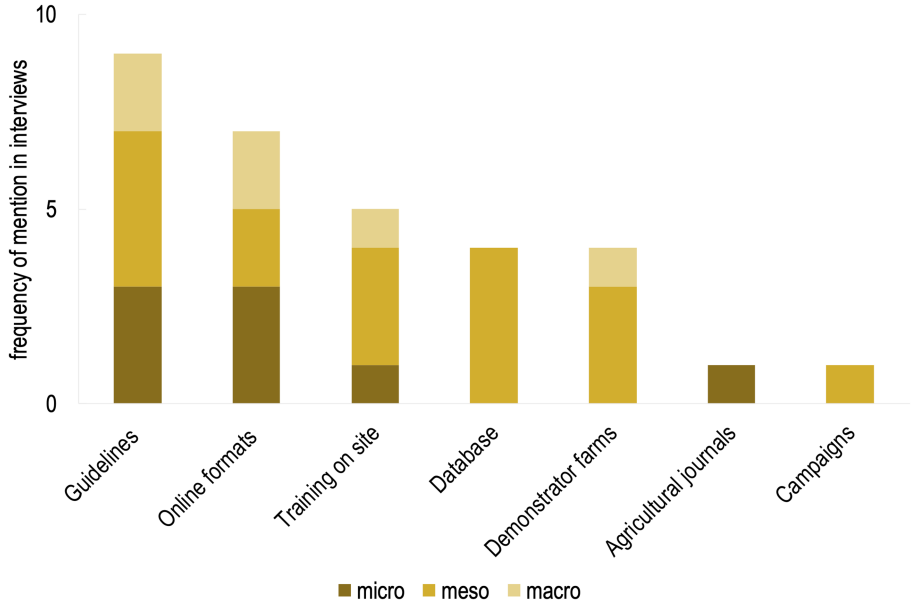

FIGURE 4
Formats interviewees mentioned to receive information about CDR. Some interviewees mentioned several formats.

> *"How can action be generated from data and facts, and the knowledge about it brought into counselling? This chain is still missing." #2_meso*

At the regulatory level of authorities, guidelines were asked for with suggestions for measurement and control mechanisms:

> *"Manuals that answer crucial questions based on science such as: How effective is it? How permanently and how validly can it be monitored or measured? That would of course be very, very helpful for the administration. It would give us better or stronger orientation." #9_macro*

Online formats are another favored format for the transfer of research results. Some appreciated that in such a format, the key points could be presented with the possibility of reaching out to those who are more interested in the topic. Short explanatory videos used in social media were also often mentioned by farmers.

> *"I always like short videos that are about three or four minutes long, where something is briefly said about how something works. I find that more illustrative, that you can visualize what it's like better than if you just read a text." #24_micro*

Actors at the meso-level expressed that they also perceive a danger with some online formats:

> *"I think we simply have too much information through social media, we have a complete surplus of information. I go on Instagram, and it feels like there are now 35 million climate researchers and environmental specialists in Germany who can immediately say what they want in seven posts on any topic because they have already read it. Nobody controls that." #2_meso*

Instead, actors of the meso level seem to instead favor online platforms or databases. Such platforms provide an overview of the pros and cons of CDR methods with links for further information.

> *"Theoretically, if you had a website showing how CDR works and simply presented the various methods and had videos and then perhaps also contact addresses where the farmers are already implementing it, so that you can perhaps contact them yourself if you want to find out more, it could help." #25_meso*

Actors of the authority level were thinking about how to better connect the data collection processes between farmers and the administration level.

> *"Thinking far into the future, online formats would be good, where the farmer enters his data into his mobile phone in the field and transmits it to the administration. There are initiatives across the federal [GERMAN] and state governments to digitize such information, but this is still a long way off." #27_macro*

Training formats on farms, where either farmers teach other farmers or researchers demonstrate findings directly on the ground, were also mentioned as suitable formats for knowledge transfer but with less intensity than guidelines and online formats.

4 Discussion

Based on our findings from the 29 interviews, we interpreted how familiar local actors from the agricultural sector in Northern Germany are with the CDR concept, what they want to know, and the formats in which they would like to receive missing information.

The concept of CDR is slowly entering the field of agricultural practices in the study region. The first time this concept was heard was 2013, as reported by an interviewee, and it peaked around 2018 and 2019. This finding corresponds to

the analysis of how English-language newspapers portrayed CDR methods between 1990 and 2021 (Minx et al., 2024). The authors discovered an increase in coverage since 2018, with a strong peak in 2021, when a wave of countries updated their climate targets.

As CDR is an abstract topic, it is not surprising that some participants were unable to fully grasp the concept of CDR. Another reason for this could be that the term is not always clearly defined in the media. Cox et al. (2024) assessed 1,500 news media articles and found that journalists did not necessarily distinguish between categories of mitigation such as avoided emissions and carbon capture and utilization. Because it is important to distinguish the specific role of CDR from emission reduction efforts, researchers in the CDR community published the first CDR status report in 2023 (Smith et al., 2023). National policy briefs were published with definitions of terms related to CDR and various categories of mitigation (Schenuit and Geden, 2023).

A common argument in the literature that discourages farmers from adopting new farming techniques is the lack of sufficient knowledge and tailored advisory services (Mills et al., 2020; European Commission, 2021). We addressed this issue by holistically collecting 22 information needs from agricultural actors about CDR-related practices. Specific CDR practices discussed the most by the study participants were soil carbon sequestration and biochar use, followed by agroforestry. This result is consistent with scientific publications on CDR, where biochar and soil carbon sequestration continue to dominate (Minx et al., 2024). Notably, questions on soil carbon sequestration were specific, whereas questions on biochar were more general. Traditional practices that contribute to soil health have long been used in agriculture, whereas biochar-enriched soils have been mostly used at an individual level and have only recently received significant attention, owing to the growing awareness on global warming and the importance of removing carbon dioxide from the atmosphere (Schmidt et al., 2021).

Existing studies on the adoption of new management practices in agriculture have one thing in common—they have all emphasized the importance of economics (Mills et al., 2020). In the present study, we also observed that the discussions had a strong economic background. Nevertheless, the agricultural actors across the levels expressed a need for information covering all six dimensions. Most statements in the interviews that led to the information needs were economical in nature. Questions regarding other dimensions were of equal importance. This finding is reflected in reviews of barriers to the adoption of farm management practices that are identified next to economic factors, such as agronomic/biophysical, socio-cultural, and institutional/regulatory factors influencing farmers' decision making (Siebert et al., 2006; Mills et al., 2020; Siebert et al., 2006; Mills et al., 2020) and that they are all interrelated (Buck and Palumbo-Compton, 2022).

Interestingly, although our study has regional characteristics, some aspects concern farmers across different regions and methods. Under the social aspect dimension, we collected questions regarding how the local community reacts to visible changes in fields diverging from traditional ones. Townsend et al. (2016) identified that farmers were concerned about the appearance of fields perceived by neighboring farms as being poorly managed as a social barrier to reducing tillage intensity.

Our regional study provides ground-level insights into the position of actors from the farmer level to the regional administration level. Empirical social science studies in the agricultural field (Buck and Palumbo-Compton, 2022) and the very few existing regional German studies on CDR (Otto and Matzner, 2024) have mostly focused on farmers as the research subjects rather than as active participants in the studies. In our study, we derived more meaningful perspectives from farmers, whose statements led to the 22 information needs, than from representatives at the meso and macro levels.

How knowledge and innovation enter the agricultural sector is a research topic that goes beyond the scope of this study. Previous studies have almost exclusively focused on farmers and less on representatives at the meso and macro levels (Šūmane et al., 2018; Rust et al., 2022) or have reported observational findings on the information channels that farmers use (Mtega, 2021; Rust et al., 2022; Nordström Källström et al., 2024). We did not find any studies that have investigated how and in what way agricultural actors wish to receive information.

Interviewees across the three levels requested the most scientific results in the form of recommendations for actions, guiding materials, or concepts. Presumably, farmers require different instructions for farm management than biochar producers or ministry representatives. However, these findings can serve as an entry point for co-developing guiding formats along a prototyping cycle (Hewitt et al., 2020) jointly between researchers and partitioners.

4.1 Limitations

While the qualitative and regional nature of this study limits the generalizability of the findings, the patterns identified here may resonate with agricultural sector experiences in comparable settings. It is also important to stress that the respondents in this study were not equally divided among the three levels, with most actors belonging to the meso level. Recruiting additional participants from the authorities was difficult. At the time of conducting the interviews, CDR was not a high political agenda in Germany yet. No explicit policy regarding CDR in general or specific CDR targets for the agricultural sector had been established in Germany or in the European Union.

Further, we cannot exclude the possibility of a social desirability bias in our study. Actors in the agricultural sector of Northern Germany are well-connected. Interviewees could have perceived some risk in sharing their honest views or that they might have withheld information, influencing the results. This may have especially been the case for the interviewees working in higher administrative institutions.

4.2 Future course of action

In this study, we explored what agricultural actors in Northern Germany need to know and how they would like to receive missing information using a one-way communication channel. The next step is to go beyond consultation and initiate

an intensive, iterative exchange with the selected agricultural actors (Steuri et al., 2022). The catalogue of information needs can serve as a starting point for follow-up transdisciplinary dialogue. Our findings are of equal importance for future research in the form of co-developed actionable knowledge between researchers and agricultural actors.

An interdisciplinary research team could go through each dimension and discuss for each of the 22 information needs whether there were already answers in the research or whether practitioners, such as farmers or politicians, would need to be consulted to answer the questions. Some questions highlight the need for further research.

However, in terms of knowledge distribution and adopting new practices, we found that farmers express relatively more trust in other farmers and associations and less trust in research institutions and agricultural authorities (Rust et al., 2022; Paulus et al., 2024). To turn the 22 information needs into action-orientated support of agricultural actors to enhance the implementation of agriculture-based CDR, it is recommended as a first step to understand the relationships between the agricultural actors in the region. A region-specific Agricultural Knowledge and Innovation System can be of great help. The concept is widely used to study processes of innovation co-development, knowledge and information sharing, and mutual learning around agricultural innovations (Knierim et al., 2015). For the study region, we learned from the regional AKIS (Bae et al., 2024) that the European Innovation Partnership of Agricultural Productivity and Sustainability EIP-AGRI initiative could be a promising entry point. The initiative has funded more than 50 innovation projects that have successfully strengthened the connection between farmers, advisors and researchers (Bae et al., 2024); however none of the funded projects so far focused on agriculture-based CDR (personal information from interviewee).

It is also highly relevant to include agricultural partitioners to take full advantage of the strengths of farmers' informal knowledge, which can be used to test scientific knowledge (Šūmane et al., 2018). In our study, some farmers expressed interest in trying new practices on their own initiative and spoke in favor of seeking greater appreciation from the scientific community for their own experiments. An increasing number of research has discussed the complementarity of informal farming and formal scientific knowledge and points to the necessity of combining them to achieve the best results (Šūmane et al., 2018; Klein et al., 2024; Moreno-Pérez et al., 2024).

We emphasize that increasing the use of CDR-related practices in the agricultural sector depends on providing actionable knowledge to farmers and their associations as a priority, and secondarily to other agricultural actors. Consequently, the co-development of such knowledge needs to build on science and a strong transdisciplinary approach, integrating actors at the eye level, from the agricultural sector and beyond.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The study was conducted in accordance with institutional requirements and local laws. Prior to the interviews, our study procedure was discussed in detail with our data protection officer as the responsible party within the meaning of Art. 4 of the EU General Data Protection Regulation (GDPR). A written consent form was drafted jointly and approved by the data protection officer before being sent to the participants. Each participant signed the consent form before participating in this study.

Author contributions

JZ: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. LG: Formal analysis, Methodology, Writing – review & editing. GT: Methodology, Visualization, Writing – review & editing. DR: Conceptualization, Methodology, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. JZ and DR contribution was funded by the German Federal Ministry of Education and Research (BMBF), projects CDRSynTra (No. 01LS2101D).

Acknowledgments

We thank the interviewees for their invaluable time by participating in this study. We thank Rodrigo Valencia Cotera for providing valuable comments on a previous version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2025.1627432/full#supplementary-material

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