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Let Us Get Regional: Exploring Prospects for Biomass-Based Carbon Dioxide Removal on the Ground

Danny Otto [1,*] and Nils Matzner [1,2,3,*]

[1] Department for Urban and Environmental Sociology, Helmholtz Centre for Environmental Research—UFZ, Permoserstraße 15, 04318 Leipzig, Germany
[2] Department of Science, Technology and Society, School of Social Sciences and Technology, Technical University Munich, Arcisstraße 21, 80333 Munich, Germany
[3] Science Studies and Innovation Research, Department of Socioeconomics, Faculty of Buisness, Economics and Social Sciences, University of Hamburg, Von-Melle-Park 5, 20146 Hamburg, Germany
* Correspondence: danny.otto@ufz.de (D.O.); nils.matzner@ufz.de (N.M.)

Abstract: In recent years, research on carbon dioxide removal (CDR) has significantly increased. Numerous studies have analyzed demonstration projects, outlined scenarios, modeled pathways, or focused on CDR's national or international governance. However, regional case studies investigating the dynamics that may facilitate or impede the broader adoption of CDR methods in spatially explicit settings are critically absent. Understanding implementation contexts on the ground is vital, and comparing them across different removal methods is essential for effectively scaling up CDR. This paper aims to address this research gap by comparatively examining the development of biomass-based CDR in three regions of Germany. Taking an exploratory approach, we conducted surveys in these regions to gain insight into stakeholder perceptions of the following six CDR methods: forest management, agriculture and soil carbon, long-lasting building materials, rewetting of peatlands and paludiculture, biochar, and bioenergy with carbon capture and storage. In this article, we present the results of the stakeholder survey, which offers multiple perspectives that can shape future studies of regional implementation and yield policy-relevant guidance. Although our research primarily focuses on the regional level in Germany, it sheds light on various conflicts, uncertainties, and potentials that are likely to be relevant for the rollout of CDR in other countries. By examining these aspects, we contribute to the broader discourse on CDR and its potential implementation.

Keywords: carbon dioxide removal; regional analysis; biomass; afforestation; peatland rewetting; bioenergy with carbon capture and storage; biochar; long-lasting building materials; soil carbon

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1. Introduction

Carbon dioxide removal (CDR) has gained relevance in authoritative assessments and international climate policy alike. Since the adoption of the 1.5 °C target in the Paris Agreement and the publication of IPCC Special Reports featuring larger amounts and more varied forms of CDR [1–3], policymakers have shifted their attention to the role of negative emissions in achieving climate goals. OECD countries have addressed CDR measures either indirectly with net zero targets or directly with concrete policy instruments e.g., [4]. In many countries, the role of CDR in achieving climate ambitions is contested; see [5] for the UK and USA, and see [6] for Sweden. On the EU level, which is highly relevant for German climate policy, positions are complex, but regulatory frameworks for CDR are being incorporated into EU climate law [7,8].

The German Climate Protection Law (2021) requires emission reductions of 65% until 2030 and climate neutrality until 2045. Thus far, the role of CDR in German climate policy has remained mainly focused on so-called 'natural sinks' in land use, land use change, and the forestry sector (LULUCF) [8]. Common but contested divisions into natural and technical removal methods fall short since they ignore the technological dimensions of supposedly natural removal options (e.g., reforestation or rewetting of peatlands) and suggest homogeneity across very different methods. Rather than being self-evident, this division is subject to different actors' perceptions and evaluations [9]. Following the IPCC classification [10], we use the characteristics of the removal process (land-based biological, ocean-based biological, geochemical, and chemical) and the storage period (decades to centuries, centuries to millennia, or ten thousand years or longer) to categorize carbon removal methods. The "Action Plan Natural Climate Protection" manifests the will of the social democratic–liberal–green government to "protect, enhance, and restore ecosystems" [9]. The governmental resolution addresses climate protection and biodiversity simultaneously by emphasizing methods such as ecosystem restoration, soil carbon enhancement, and forest management.

However, the coalition agreement of the current German government acknowledges the necessity of "technical negative emissions technologies" [10], and a strategy for carbon management that includes regulations for carbon capture and storage (CCS) and carbon capture and utilization (CCU) is being developed [11]. The German Ministry for Economic Affairs and Climate Action (BMWK), a decisive player in German CDR policy making, has started to include both "natural" and "technical" CDR in their climate change mitigation planning. For more on the role of the BMWK, see, e.g., [8,12,13]. Additionally, analyses by various interest groups assess the need for a combination of land-based biological, geochemical, and chemical CDR options, e.g., [14,15].

The Kohlendioxid Speicherungsgesetz [16] is of particular relevance for some of these methods in the German context since it prohibits the storage of CO_2 in Germany—either offshore or onshore. Thereby, it limits the portfolio of possible CDR methods since options connected to carbon capture and storage (CCS), such as bioenergy with CCS (BECCS), e.g., [17], or direct air capture with storage (DACCS), are currently not legally feasible [18,19]. The latest evaluation report on the German CO_2 law [20] suggests revising the legal framework for CCS in order to ensure planning security. The German government is examining changes to the law as well as amendments to the London protocol to enable (a) carbon storage in Germany and (b) transport to other European countries [20].

Scientific research on CDR has increased immensely in recent years. For reviews, see [21–23]. There is work on the role of CDR in climate models, national and international governance, environmental impacts, and the analysis of demonstration projects, e.g., [23–30]. Despite this plethora of research, there is so far limited knowledge of the regionally-specific deployment of CDR methods from a comparative point of view, e.g., [31]. Some studies include stakeholders or the public to discuss possible future implementations of CDR, e.g., [32–34]. Others compare the perception of different CDR options and their acceptability in the eyes of the public, e.g., [35,36], or experts, e.g., [37]. Nevertheless, these articles do not study deployment contexts on the ground.

However, it is of crucial importance to take regional and local considerations into account, as these are the settings in which the actual deployment of CDR will take place. Without interested and committed stakeholders and local publics, a broad rollout of CDR will not materialize. It is therefore necessary to understand their concerns and needs, map emerging networks and initiatives, and take a comparative stance to understand how synergies and trade-offs between different CDR options are perceived. Recently, large research initiatives in different European countries, e.g., the UK greenhouse gas removal demonstrators, [38], or CDRterra in Germany [39], have started to investigate the potentials of portfolios of CDR methods and to study their implementation contexts and impacts in specific settings.

Our study is part of the CDRterra initiative in Germany (the German Federal Ministry of Education and Research funds the CDRterra project consortium (https://cdrterra.de/en (accessed on 4 March 2024)). This study is conducted as part of the BioNET project (https://www.ufz.de/index.php?en=49066 (accessed on 4 March 2024)), which is part of CDRterra. See funding) and contributes to filling the outlined gap in research by comparatively investigating the spatially explicit context of biomass-based CDR (bioCDR) deployment in three focus regions in Germany (Mecklenburg-Western Pomerania, Central Germany, and Rhine-Neckar). We draw on surveys that inquire about knowledge, potential, and the future of bioCDR for an explorative mapping of regional stakeholder perceptions on six groups of CDR methods (forest management, agriculture and soil, long-lasting building materials, rewetting of peatlands and paludiculture (herein understood as the "cultivation of biomass on wet and rewetted peatlands"; see e.g., [40,41]), biochar, and bioenergy with carbon capture and storage).

Conceptually, we understand CDR methods as technologies that are imagined to capture and store CO_2, removing it from the atmosphere in order to mitigate climate change. On one hand, this refers to technologies like BECCS, paludiculture, or biochar that do not yet exist at scale but are deemed able to significantly contribute to CO_2 removal in the future [26,31,42]. On the other hand, already established practices such as forest management, agriculture, or sustainable building are being reimagined in light of climate change impacts (e.g., droughts, increased temperature, parasites) and new goals that have not been a focus before—namely the increased capture and secure storage of CO_2. As such, CDR is part of larger socio-technical imaginaries, meaning "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" [43]. In the case of CDR, this refers to imaginaries of mitigating climate change by introducing promising technology options (for instance, those stabilized by their prominent inclusion in models), thereby framing and performing particular climate futures [44–46]. The associated governance strategies and implications are critiqued for their potential to delay decarbonization, e.g., [47,48], or the possible negative impacts of CDR on ecosystems, e.g., [49,50]. While there is a growing amount of literature addressing this topic, the debate remains on a national or transnational level.

We argue that we need to study the regional and local translations of these imaginaries since sustainability transformations are rooted in concrete, regionally-nested practices and ways of thinking.

Therefore, we use our survey data to map how CDR is perceived, which initiatives exist, and how networks emerge in different environmental, political, social, and technological settings. This will yield insights into the scope of existing collaborations and imagined futures in our focus regions, as well as into implementation barriers. Beyond stakeholder networks, initiatives, and interactions, we also study how different CDR options are discussed in usage cascades of biomass. This refers not just to synergies, trade-offs, or conflicts arising from the competition for biomass between bioCDR methods but also addresses the potential organization of bioCDR along value and supply chains.

This article starts by explaining the research approach of the stakeholder survey. Afterwards, we present the survey results regarding stakeholder knowledge and existing initiatives on bioCDR in the focus regions. We document the perceived potentials of individual technologies, the interactions of multiple bioCDR options, and future prospects in light of barriers and drivers. Ultimately, the discussion and conclusion sections highlight the important problems (such as insufficient regional support or missing regulatory frameworks) and outline policy-relevant advice.

2. Materials and Methods

We identified three case-study regions along a north–south and east–west gradient across Germany. We selected these cases to represent different regional characteristics, ranging from areas with a land-use-based economy in the north to more industrialized regions in central and southern Germany [51–53]. Regional specificities, such as peatland rewetting only being possible in northern Germany and the presence of industrial infrastructure for BECCS in southern Germany, were the main criteria. Stakeholders in these regions were identified based on the potential relevance of biomass-based CDR methods from the perspectives of public policy, private entrepreneurs, and civil society. Contacted stakeholder groups include actors from the public sector (ministries and public agencies related to land use, forestry, regional development, etc.), the private sector (providers and users of biomass, the energy sector, the bioeconomy, and related industrial processes, etc.), and civil society (in particular non-governmental organizations (NGOs) with regional presence).

The selection of regions and stakeholders is not representative of the entire geography of Germany; it addresses the particular context of the respective regions. However, issues of national relevance apply to all three regions, such as policies and regulations related to CDR in general and certain CDR methods in particular. We therefore expect this selection to differentiate the topics according to regional and national relevance.

Our sample was built to map the diversity of stakeholders in biomass-based CDR in the respective regions (see Figure 1). The selection was based on a combined approach of literature, recommendations by interdisciplinary scholars from our project, and stakeholder recommendations ("snowball sampling"). We contacted 63 stakeholders in total. The online survey was completed by 34 participants between January and April 2023 in the three German regions: Mecklenburg-Vorpommern (MV, n = 11), Mitteldeutschland (MD, n = 19), and Rhein-Neckar (RN, n = 14). The sample represents rural regions (MV) as well as urban and industrialized regions (MD and RN). The irregular distribution among stakeholder groups and regions resulted from the following two problems: First, bioCDR is still in an early stage in Germany, where not all relevant stakeholders have already dealt with this novel approach. Second, some stakeholders are reluctant to respond—even to repeated requests—because of the politicized nature of CDR. Consequently, we are dealing more with a data acquisition problem than a selection bias.

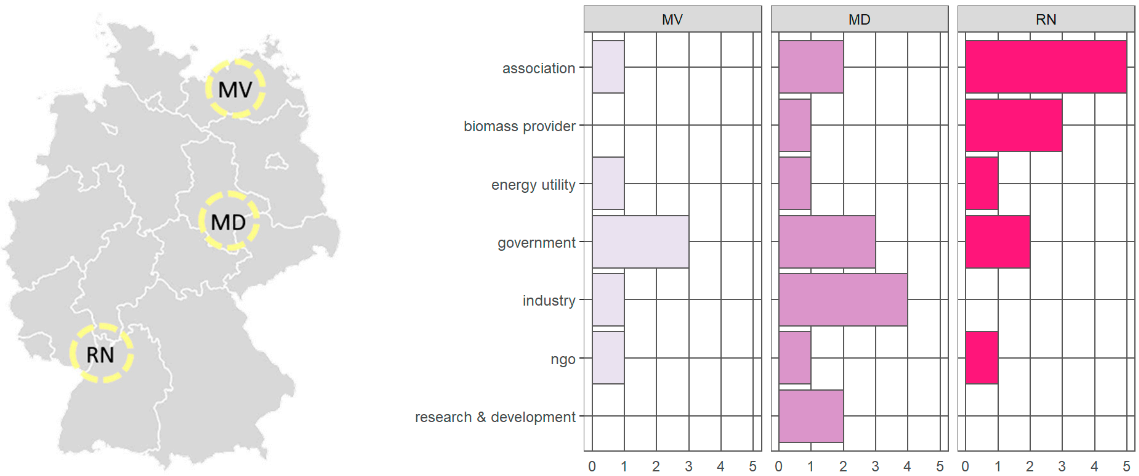

Figure 1. Overview of focus regions.

We developed the questionnaire based on existing literature on the perception of different carbon dioxide removal technologies or components that are relevant for them (such as CCS). An overview of the questionnaire sections is provided in Table 1 (see Appendix A Table A1 for the full questionnaire). In the first section, we asked for knowledge of CDR overall and more precisely for knowledge of particular biomass-based CDR method groups (forest management, peatland rewetting, paludiculture, soil carbon, biochar, and BECCS). Since we selected the stakeholders according to their connection to one of the bioCDR methods of interest, we had to consider that not all were knowledgeable about all of these options. Therefore, we approached the questionnaire design in parallel to surveys on little-known topics and developed it as an "informed questionnaire", e.g., [35,54–56]. An information box for each method was provided with a 'working definition' in order to enable all participants to respond to the next section of questions focused on the relevancy of CDR (see Table 2).

Table 1. Questionnaire overview with references.

Section	Topic	References
1	Knowledge regarding CDR and individual bioCDR methods	[57–61]
2	Relevance of CDR and individual bioCDR methods for the stakeholder's field of work	[37,57]
3	Future potential and challenges for bioCDR	[37,62–64]
4	Regional cooperation and CDR networks	[5,65]
5	Trust related to CDR	[56,66,67]

Table 2. Overview of bioCDR method groups (for detailed information on the CDR methods, see [68]).

bioCDR Method Group	Short Description
Forest management	Afforestation of new forest areas and various measures in existing forest areas can help remove carbon dioxide from the atmosphere and store it.
Peatland rewetting	Most of the peatlands in Germany have been drained for agricultural use. The drained peatlands emit large quantities of greenhouse gases every year. Rewetting peatlands can reduce these emissions and promote the formation of new peat by the vegetation, which absorbs carbon dioxide from the atmosphere.
Paludiculture	The wetlands of rewetted moors can be used for agriculture and forestry (paludiculture originates from "palus", Latin for "marsh/swamp"). The biomass obtained (e.g., reeds) can be used for energy production (see BECCS) or as building materials.
Soil carbon	Agricultural measures, such as soil-conserving cultivation and adapted crop rotation, can help to increase the carbon content in the soil in the long term and thus remove carbon dioxide from the atmosphere (carbon farming).
Biochar	Biomass from agriculture and forestry can be carbonized via pyrolysis. In this process, the biomass is not completely burned, and charcoal is formed. This biochar can be incorporated into the soil (e.g., in fields), whereby its carbon compound remains in the soil for a long time.
Long-lasting building materials	Materials made from renewable raw materials (wood, reed, etc.) can be used in a variety of ways in construction (e.g., as wooden structures and insulating materials). In addition, products made from renewable raw materials (e.g., biochar) can be added to other building materials (e.g., concrete). In this way, carbon dioxide from the atmosphere is bound in biomass and stored in long-lasting building materials.
BECCS	Biomass from agriculture and forestry (especially biogenic residues and waste) is used in bioenergy plants (e.g., biogas, biomethane, gasification, combustion, and bioethanol plants) and converted into heat, electricity, or fuels. These plants could be equipped with technologies that capture the carbon dioxide from the exhaust gases. There are plans to store this captured carbon dioxide underground (for example, in old gas reservoirs under the North Sea). The capture and storage part is also known as carbon capture and storage (CCS).

In addition to a quantitative evaluation of the relevance of the CDR and biomass-based CDR methods for the stakeholders' respective fields of work, the participants were asked to explain their reasoning in an open question. We anchored the assessment in the stakeholders' concrete field of work in order to encourage a more regional evaluation. Section 3 focused on potential and asked for relevant challenges to bioCDR deployment (an open question) as well as future relevance. The fourth section was dedicated to actors that the stakeholders cooperate with for CDR deployment. In the fifth and final section, we asked respondents to state their level of agreement with five statements related to trust. As trust is a multifaceted issue that goes beyond trust in individual actors [67], we included statements that refer to trust in CDR technologies, political support, scientific knowledge, public support, and trust in cooperation with companies.

Due to the small number of surveys, we mainly conducted descriptive statistics and qualitative analysis of the open-ended responses. As most of the participants provided ample details in the open questions, we were able to conduct a qualitative content analysis [69] of this material. The coding scheme was devised to capture relevance, potential, challenges, and existing initiatives for regional bioCDR deployment (including existing networks).

3. Results

In this section, we present the results of our stakeholder survey in three subsections. First, we will outline the feedback regarding knowledge of CDR technologies. Next, we present the outcomes of the quantitative and qualitative assessments of CDR relevance and the current challenges for deployment. Stakeholder perceptions of already existing networks, trust, and potential for the future of bioCDR are shown in subsection three.

3.1. Knowledge of CDR Technologies

The average knowledge of bioCDR technologies among stakeholders is midrange for most technologies. Figure 2 presents the self-assessed knowledge of CDR and different bioCDR options. It displays the different technologies, from the one with the highest mean self-assessed knowledge on the left to the one with the lowest mean on the right. Our analysis reveals that respondents assess their knowledge of CDR technologies on various levels, between expert and layperson, without a single technology appearing well known by all stakeholders. This is not surprising given the diverse nature of CDR and the varying levels of expertise required for each type. For specific bioCDR methods, results are different; we see that the sample includes stakeholders with self-assessed expert knowledge for each option. However, when comparing the various bioCDR methods, respondents indicate a higher level of familiarity with topics such as forest management, soil carbon, building materials, biochar, and rewetting. In contrast, their knowledge appears to be relatively less extensive for BECCS and paludiculture.

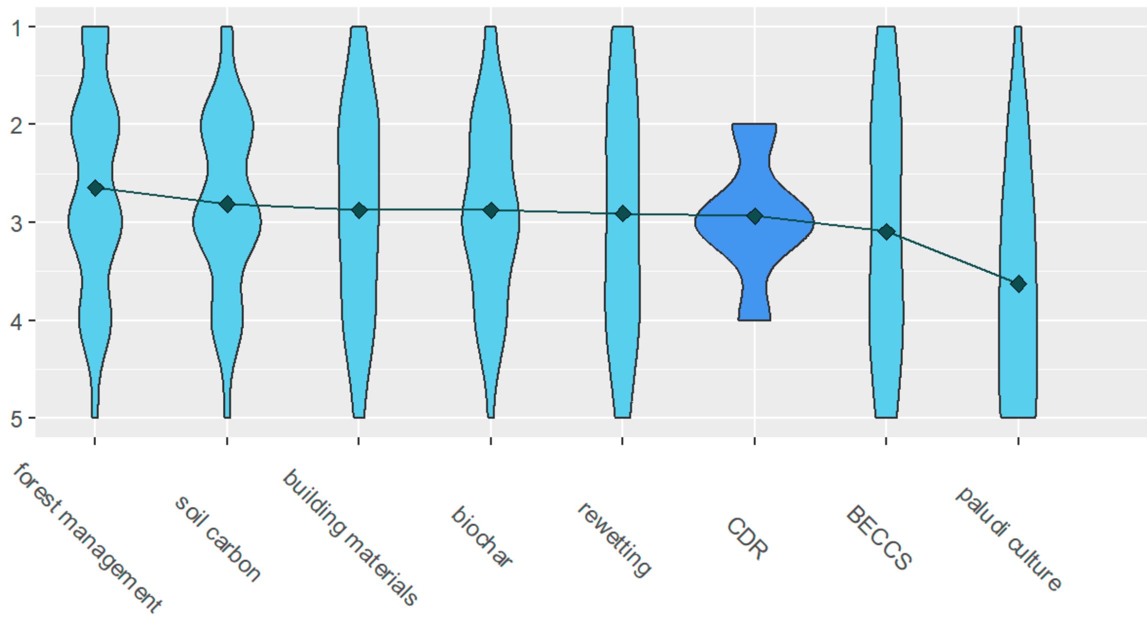

Figure 2. Knowledge of CDR technologies. Question: "How much do you know about CDR and the listed bioCDR technologies?". Response categories: 1—very much, 2—a lot, 3—something, 4—a little, and 5—nothing. Mean values are depicted in plaids. Overall CDR knowledge in dark blue. $n = 34$.

3.2. Relevance of CDR Technologies and Challenges

Concerning the relevance of CDR technologies, we find that most of the respondents in our sample consider CDR methods relevant overall (see Figure 3). Looking beyond the quantitative assessment, we find that the relevance stems mainly from the following two streams of argument: First, CDR is crucial for achieving climate goals, for instance, because it is necessary to deal with residual emissions. Second, CDR is important because of the environmental co-benefits associated with CDR technologies (e.g., biodiversity, business cases). Although both arguments are linked to sustainability goals, they differ in their emphasis on different aspects, as the following quotes show:

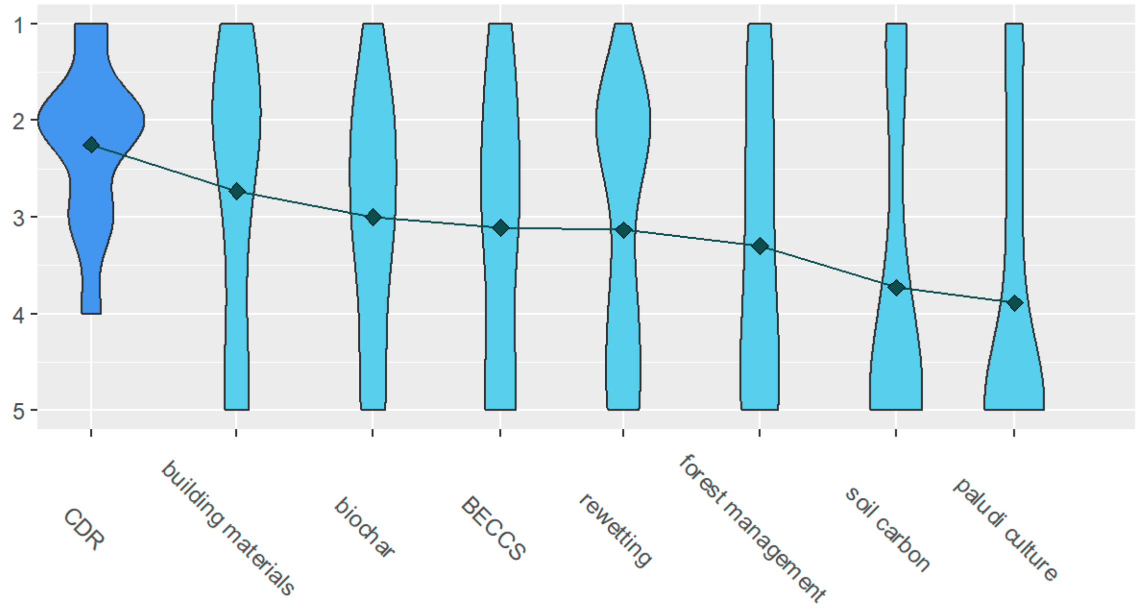

Figure 3. Relevance of CDR technologies. Question: "How relevant are CDR and the listed bioCDR technologies for your field of work?". Response categories: 1—very relevant, 2—relevant, 3—neutral, 4—hardly relevant, and 5—irrelevant. Mean values are depicted in plaids. Overall CDR relevance in dark blue. n = 34.

Stream 1:

"Negative emission technologies are the only way to achieve a balanced CO_2 balance worldwide in the long term."

(Energy Utility 1)

"Negative emissions are essential to achieving agreed climate targets."

(technology development 1)

Stream 2:

"Negative emission projects are more interesting because of their co-benefits; the CO_2 that is bound in a wooden house is not a big deal, but the CO_2 that is not released if you do not use concrete is highly interesting. Reforestation, renaturation of peatlands, and hummus formation will not reverse climate change but are great steps towards biodiversity and sustainable agriculture."

(eNGO 1)

Core challenges that are mentioned for CDR are an expected lack of public and political support resulting from, among other causes, land-use conflicts and the feared loss of property values. Furthermore, high production costs compared to fossil- based products and the lack of an efficient CO_2 market accompanied by trustworthy certificates hamper the development of CDR on the ground. Likewise, persistent research gaps and a lack of practical implementation guidelines are perceived as obstacles to the expansion of CDR.

Taking a closer look at specific bioCDR methods, Figure 3 displays different options, from those with the highest stakeholder-attributed relevance at left to the lowest attributed relevance at right. Overall, we find that stakeholders assess individual bioCDR options as less relevant compared to CDR in general. Long-lasting biomass-based building materials are seen as more relevant in comparison to the other bioCDR methods. The relevance of more technical methods (building, biochar, and BECCS) is perceived as neutral on average, whereas rather "natural" CDR options (rewetting, forest management, soil carbon, and paludiculture) received lower relevance scores.

Long-lasting, sustainable, and biomass-based building materials are deemed to be the most relevant option among the listed methods. In the open question section, stakeholders argue that long-lasting biomass-based building materials have high potential for carbon storage, yet the availability of materials is limited. Good options exist for biomass input connected to sustainable forest management and paludiculture, but such cascades are limited by technical challenges arising, for instance, due to the calibration of building material production machinery mainly for specific kinds of biomass (e.g., hardwood).

Biochar is linked to building materials in several applications. Stakeholders express that its relevance is due to its versatility. Biochar may be used for alternative construction materials (for instance, by replacing mineral additives in building products). It also has usage options in agriculture and forestry, for example, as "bio-fertilizer" and for enhancing growth through improved water storage. Furthermore, respondents identify an economic potential because of certificates for carbon storage that are being developed. Our respondents mention concerns about the negative impacts of biochar on the environment (e.g., pollutant entry) and open research questions on some uses of biochar as well as the persistence of carbon storage.

The relevance of BECCS is evaluated as slightly below neutral, indicating that stakeholders are torn in regards to this technology. Some argue that BECCS has potential because different kinds of biomass can be fed into the bioenergy process, meaning that it can be positioned at the end of biomass usage cascades—potentially even coupled with pyrolysis processes for biochar production. Some do not deem BECCS relevant since they see CO_2 utilization as a much more promising avenue: instead of storage, it enables further use of CO_2 as a resource. Many stakeholders are skeptical about the political and societal perception and feasibility of BECCS and question whether transport infrastructure (e.g., CO_2 pipelines) will be available in the near future.

Likewise, rewetting of peatlands received mixed assessments, and its relevance is seen as "neutral" in the mean. On one hand, rewetted peatlands are seen as an important CO_2 sink. On the other hand, stakeholders mentioned land-use conflicts related to agricultural land, possible needs for settlement relocation, and an increased chance of diseases related to mosquitoes. Paludicultures are directly linked to rewetted peatlands and were discussed along similar lines. However, paludiculture's relevance was rated lower, with a mean value of "hardly relevant". Some stakeholders mention that they were not previously familiar with the term. Others indicate the role of reed plants for building materials (e.g., insulation materials) or the potential of paludi biomass for energy production and as a feedstock for pyrolysis. Two stakeholders explicitly question the climate change mitigation potential of paludiculture and argue that the negative emissions connected to paludi "are used for marketing purposes" (Energy Utility 2).

Forest management and soil carbon are perceived as comparably less relevant. Stakeholders note that sustainable forest management—meaning wood being taken out of the forest at a sustainable rate and used for building materials and energy production—is the central way in which forestry secures the woodlands as CO_2 sinks and contributes to carbon removal. While forest decommissioning and its conflict with sustainable forest management were mentioned, the stakeholders attributed more relevance to managed forests. A lack of knowledge of climate-resilient tree species among practitioners, forest owners, and scientists, regulatory uncertainties, and the lack of economic prospects while negative emissions are not formally certified are listed as challenges for this bioCDR method.

The open questions received fewer references to soil carbon, meaning bioCDR options are connected to agriculture. Stakeholders only mention economic potential if negative emissions through humus buildup can be properly certified (or certifiable) and if co-benefits such as increased biodiversity can be taken into account. The major challenge is the limited recognition of the actual CO_2 binding achieved in soils.

To offer a preliminary summary regarding relevance, potential, and challenges, every bioCDR option in our research focus was known to stakeholders as bringing various challenges. Even seemingly straightforward methods, such as afforestation or the use of long-lasting building materials, have their own barriers. Although CDR's relevance is considered high, there are no "low-hanging fruits" or "silver bullets" that could be highlighted.

3.3. Networks for Trust in and Future Potentials of CDR Technologies

Since we aimed to understand the implementation of bioCDR methods on the ground in our case study regions, we were interested in the existing networks and future developments of CDR technologies that our stakeholders expected. By asking about existing cooperations, we find that the networks of actors vary across the regions and for bioCDR options. The networks displayed in Figure 4 are assembled by combining individual cooperation statements. For example, an actor from the government could claim to be working with NGOs even though NGOs were scarce in the sample. By combining the regional networks, we obtain a network for all regions together. Figure 4 shows a cooperation network, whereas the 'all'-network is a combination of the three regions. The 'all'-network shows a strong interconnection of all actors with a majority of governmental actors (eight links to other actors). The strongest connection exists between the government and research and development. There is an established and operating network of governmental actors, scientific institutions, landowners, local NGOs, and energy utilities in MV—a rural region—on peatland rewetting and paludiculture. We do not see a paludi-specific network in other regions. For other CDR methods, however, such technology-specific networks are not reported in MV. Stakeholders in central Germany (MD) mention more connections to actors related to the forestry and building materials sectors for the development of CDR in the region. Beyond that, their list of networks remains on a more generic level and includes technology developers, planning agencies, companies, universities, scientific institutions, and ministries on the federal and national levels. A rather similar picture emerges based on stakeholder feedback in the Rhine-Neckar region (RN). We find very specific lists of actors in networks related to biomass-based building materials and forestry. Other networks, again, remain generic, with politicians, scientific institutions, companies, ministries, and, in one case, environmental NGOs (eNGOs). On an overarching level, we see that eNGOs are hardly mentioned as part of the regional bioCDR networks.

In addition to cooperation networks, we asked for trust in various actors and technologies as an important factor for CDR perception and for future investments (see Figure 5). We find that 75 percent of the stakeholders indicate trust in scientific research on CDR. More than 50 percent agree with the statement that CDR methods are a means to securely store CO_2 for the long term. Those disagreeing are eNGOs and energy utilities with an interest in the utilization of CO_2 rather than its storage. Furthermore, we asked for trust in the support of actors (publics, politicians, and companies) and the possibility to collaborate with them on CDR. The results indicate that 60 percent of the stakeholders in our sample trust the collaboration with companies on CDR. In comparison, trust in political support (about 30 percent) and public support (about 20 percent) for CDR is limited. Again, we find eNGOs to be skeptical about the support of the listed actors.

Turning to the future expectations expressed by the stakeholders, three findings emerged: 1. With regard to the future, stakeholders agree that the imminent reduction of CO_2 emissions should be the first priority. CDR is not expected to solve any problems if CO_2 emissions are not drastically reduced. 2. Nevertheless, stakeholders perceive the future relevance of CDR to be greater than its current importance. Participants cite its potential contribution to achieving temperature targets and the perceived "inevitability" of implementing CDR due to unavoidable residual emissions as reasons for this assessment. 3. The majority of stakeholders assume a growing relevance of CDR for their own sphere of action, even if many challenges may remain. We find that some of the participants are already investing in bioCDR and aim to establish this as a new secondary or core business.

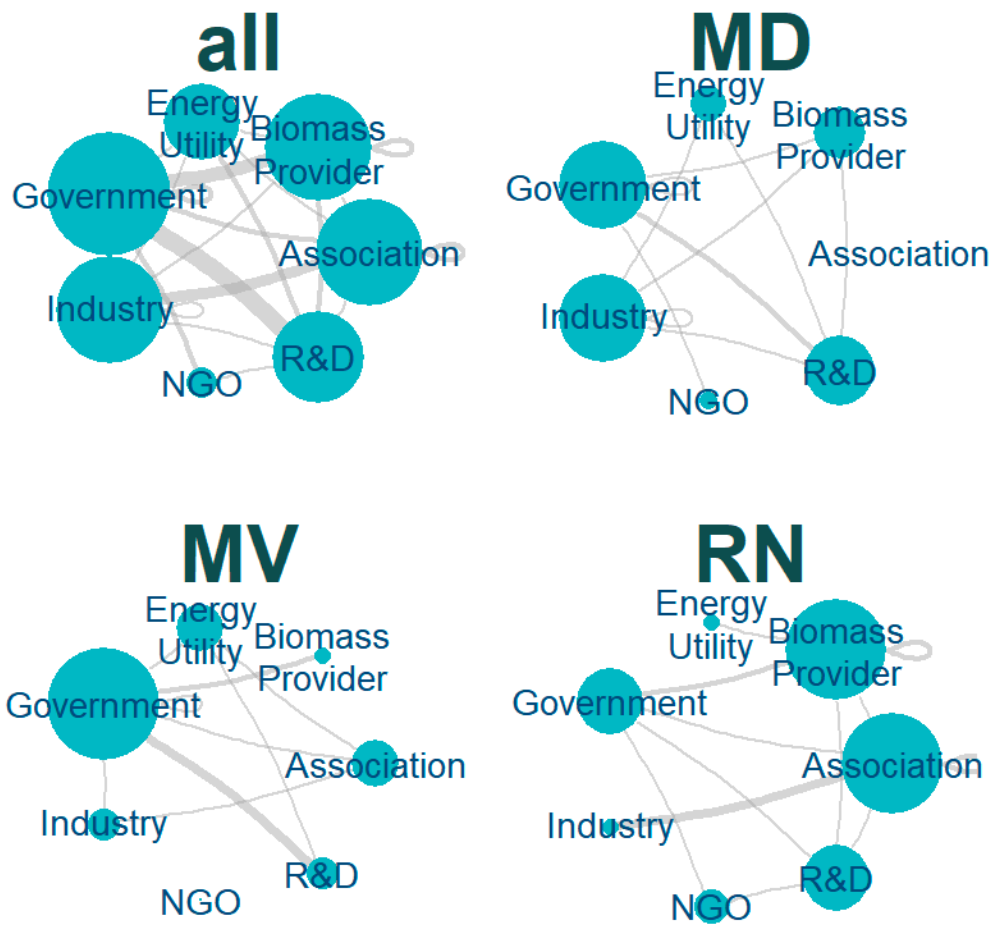

Figure 4. BioCDR networks per region (three regions next to each other).

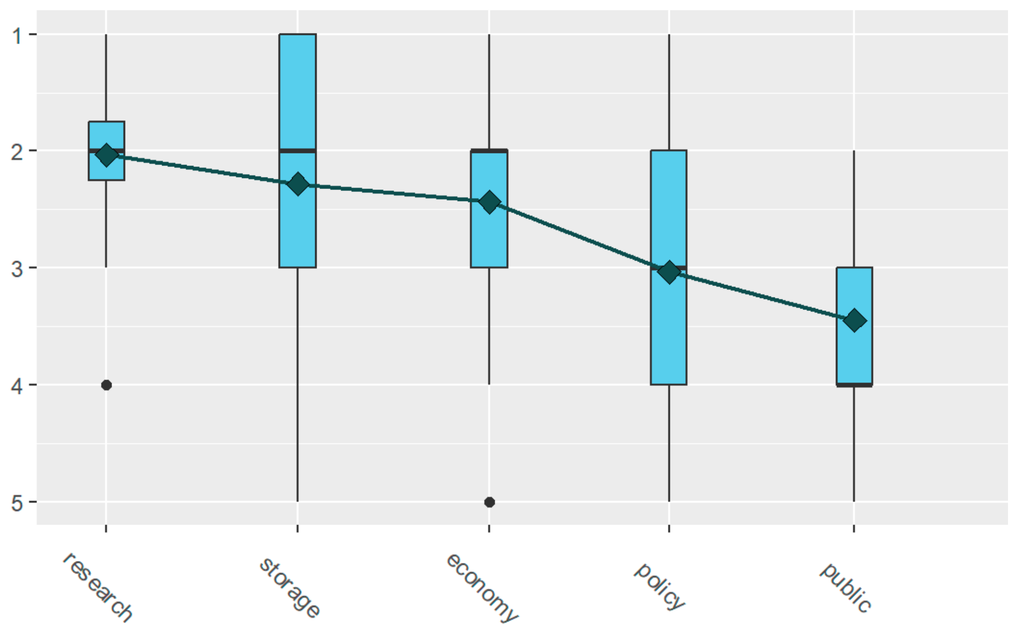

Figure 5. Trust of stakeholders related to CDR. 1—very high trust, 2—high trust, 3—neutral, 4—low trust, and 5—very low trust. Mean values are depicted in plaids. n = 34.

4. Discussion and Conclusions

In this paper, we have explored stakeholder perceptions of CDR, especially bioCDR, on a regional level. Since most of the existing research remains on a national or international level, this spatially explicit approach was much needed, e.g., [31], in order to understand the concrete conditions and contexts in which CDR deployment will take place. Such a task becomes more crucial as CDR moves from models to governance issues and on to the question of successful rollout [33,70]. Based on a survey with stakeholders related to bioCDR in three case study regions, we collected initial insights into regional interpretations of larger socio-technical imaginaries of CDR and their role in climate change mitigation [22,44,46].

The results of our assessment provide valuable insights that can contribute to helping understand the development of CDR initiatives and shaping policy and governance practices. We draw multiple key messages from our results and suggest the need for further research, as stated below:

1. In our stakeholder evaluation focused on seven bioCDR methods, we discern regional focal points for CDR initiatives. Noteworthy examples include the emphasis on rewetting and paludiculture in MV, forestry and agriculture in RN, and forestry and building materials in MD. The responses from the interest groups show that networks already exist for these regional focus methods. However, it is important to note that we are unable to determine the extent of collaborations and exchanges based on our survey; future research is needed here.
2. While the aforementioned CDR methods show existing collaboration networks and are nearing deployment (or are deployed on small scales), we do see stark differences in the technical readiness and the societal embeddedness of the methods [71]. It remains uncertain how close they are to deployment and upscaling. The local engagement with CDR options made progress in its implementation discussion, although many hurdles exist.
3. In light of the stakeholder responses, it became clear that no single CDR solution can be deemed low-hanging fruit. Instead, we find that all options, in the eyes of the stakeholders, come with their own set of challenges and potentials. This indicates the need for a portfolio approach to CDR that takes the strengths and weaknesses of individual methods as well as regional context conditions into account to find a balanced and spatially-nested carbon removal strategy. In a parallel line of argument, CDR portfolios have been suggested in recent CDR reports, e.g., [23,72].
4. The challenges highlighted by the stakeholders include the necessity of clarifying political support and regulatory frameworks for CDR, which are frequently cited as barriers to development in the regions. This resonates with current research on the governance of CDR, e.g., [28,73].

Our findings, thus, underscore the complexity of CDR implementation, emphasizing the importance of a nuanced, region-specific, and portfolio-based approach. Although bioCDR technologies are required for many mitigation pathways [74], their socio-technical feasibility is still uncertain. At this early stage of CDR development and implementation in Germany, our survey results show a differentiated picture for CDR measures, topics, and regions. The relevant stakeholders expressed the high potential of many of these measures, but at the same time saw many obstacles to implementation in Germany, such as the lack of political and social support (see Figure 5 regarding trust). However, important stakeholders from government, industry, eNGOs, and other sectors are not yet fully engaged with bioCDR. Consideration of technical, social, and regulatory aspects with the active involvement of stakeholders will be of central importance for CDR's successful introduction.

From our first exploratory assessment, we can derive multiple open research questions for more in-depth investigations. As such, it would be necessary to have more detailed exchanges with stakeholders, as a survey can only put spotlights on issues but not explore them sufficiently. It would also be important to bring stakeholders together for joint evaluations of bioCDR options' co-benefits, potential synergies, and challenges (e.g., regional competition for biomass). Furthermore, there is a need to better understand misconceptions that became visible in the survey, such as the fear of malaria related to the rewetting of peatlands or the assumption that bioenergy production in itself is already CDR. Discussing these ideas and learning about their foundations will be important to counter expectations and reflect on risk communication that takes rational and emotional responses to deployment plans into account, e.g., [75,76].

It is important to stress that our results should be considered with some limitations that derive from the sampling approach and stakeholder feedback. First, we did not get responses from all stakeholder groups in the same proportion in all regions. This can introduce a bias into the data. While we strived to limit and reflect this, we can ultimately only discuss the perspectives of stakeholders who were willing to join the study. Since we encountered difficulties in recruiting eNGOs, their point of view on CDR is underrepresented in our sample. This hesitancy and lack of workforce availability to respond to research contribution requests is a finding in its own right and would be interesting to follow up on in empirical eNGO research [77,78]. It was also not possible to gain access to the individual positions of farmers, who will eventually be central to CDR measures related to agriculture. Second, a more in-depth and long-term stakeholder process could enable a more comprehensive understanding of regional CDR deployment contexts. A combination of qualitative interviews and workshop formats would allow for more detailed expressions and descriptions of enabling and limiting factors for CDR in spatially explicit settings. Lastly, the small sample size restricted us to presenting only descriptive findings and limited the generalizability of our results. Parallel to current expert surveys [37], it would be worthwhile to approach the regional implementation of CDR with a broader survey strategy.

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Appendix A

Table A1. Questionnaire (translated to English).

V1	Please indicate on the scale below how much you know about negative emissions technologies. 5-point scale (very much—nothing at all)
V2	Are negative emissions technologies relevant to your field of work? 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V2.1	Open question: Please explain the relevance
V3	Please indicate to what extent you are familiar with the following methods for generating negative emissions 5-level scale (very much—nothing at all)
V3.1	Forest management (e.g., afforestation, expansion of forest area)
V3.2	Rewetting of peatlands
V3.3	Paludi culture
V3.4	Bioenergy with carbon capture and storage (also known as BECCS)
V3.5	Biochar

Table A1. *Cont.*

V3.6	Changed use of soils in agriculture (e.g., year-round ground cover, agroforestry)
V3.7	Utilisation of durable building materials made from biomass (e.g., insulation or building materials based on renewable raw materials)
V4	Please indicate to what extent the following processes for generating negative emissions are relevant to your area of work.
V4.1	Forest management (e.g., afforestation, expansion of forest area) 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.1.	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.2	Rewetting of peatlands 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.2.	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.3	Paludi culture 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.31	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.4	Bioenergy with carbon capture and storage (also known as BECCS) 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.4.	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.5	Biochar 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.51	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.6	Changed use of soils in agriculture (e.g., year-round ground cover, agroforestry) 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.6.	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
V4.7	Nutzung langlebiger Materialien aus Biomasse (u. a. auf nachwachsenden Rohstoffen basierende Dämm- oder Baustoffe) 5-point scale (very relevant—relevant—neutral—hardly relevant—irrelevant), I don't know
V4.7.	Open question: Please enter further information on the relevance of the NET process/negative emission technology here.
	What obstacles do you see to the expansion of NETs that are relevant to your area of work? (open question)
V5.	How do you rate the future relevance of negative emissions technologies? 5-point scale (very high—neutral—very low), I don't know
V5.1	Open question: Please give reasons for future relevance.
V6.	Open question: Please name stakeholders you work with on negative emissions technologies.
V7.	To what extent do you agree or disagree with the following statement? 5-point scale (fully agree—partly agree—partly disagree—don't agree at all); I don't know
V7.1	I trust the long-term storage of CO2 through negative emission technologies
V7.2	I trust in the political support for negative emission technologies
V7.3	Scientific research provides reliable findings on negative emission technologies
V7.4	I trust in the support of the population for negative emission technologies
V7.5	I have trust in the cooperation with companies regarding negative emission technologies.
V8.	Open final question: Is there anything else you would like to tell us?

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