



Contesting land-based greenhouse gas removal futures: Emerging sociotechnical visions of biochar in UK agriculture

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Abstract

This paper critically examines the emerging sociotechnical visions of biochar within UK agriculture, focusing on its potential role in greenhouse gas removal (GGR) and the broader net zero agenda. Agriculture is framed as both a significant source of greenhouse gas emissions and a unique sector capable of acting as a carbon sink, positioning it at the heart of debates about climate change mitigation. The paper adopts a sociotechnical visions framework to illuminate how stakeholders align with, contest, and propose alternatives to the dominant net zero sociotechnical imaginary. We identify two overarching sociotechnical visions of biochar in UK agriculture. The first is a sociotechnical vision of greenhouse gas removal through biochar produced at scale and applied to agricultural land, detailing both farmer alignment with and contestation of this approach. The second is a sociotechnical vision of biochar for multiple on-farm benefits, including farm business benefits, enhanced agricultural production and improved on-farm biodiversity. The analysis shows that the future of biochar in UK agriculture is characterised by diversity and contestation, requiring governance frameworks that accommodate multiple, sometimes competing, sociotechnical visions. This pluralism offers opportunities for more just, inclusive, achievable, and transformative pathways for biochar in UK agriculture. Additionally, the paper contributes to the literature on sociotechnical imaginaries and sociotechnical visions by foregrounding the dynamic interplay and negotiation between top-down institutional imaginaries—such as net zero—and emergent, grassroots visions developed by farmers and other agricultural stakeholders.

Keywords Biochar · Sociotechnical visions · Sociotechnical imaginaries · Agriculture · Greenhouse gas removal (GGR) · Net zero

Introduction

Within the context of climate change, agriculture is typically framed as one of the hardest sectors to decarbonise, along with shipping and aviation (Buck 2021; Markusson et al. 2020; Waller et al. 2020). However, unlike these other sectors, agriculture is uniquely placed to also remove and store carbon from the atmosphere and therefore contribute to climate change mitigation and net zero targets including through land-based greenhouse gas removal (GGR)

approaches. One of these approaches is biochar, a material produced by a thermochemical process called pyrolysis, which sequesters carbon from biomass source materials for potentially hundreds or thousands of years. Biochar is attracting increasing levels of policy, scientific and commercial interest across multiple jurisdictions (Carbon Gold 2025; Senadheera et al. 2025; Singh et al. 2025; TerrAffix 2025). In the UK, it is one of five demonstrator projects funded by the public sector under the £31.52 million Greenhouse Gas Removal Demonstrators programme.

Agriculture variably features within and between the arenas of biochar interest¹ as agricultural land can be

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¹ Outside of agriculture biochar can be used for land remediation and carbon storage in quarries, embankments, and mines (TerrAffix 2025). It can also be incorporated into road construction materials, cement, concrete, textiles, paper, and ceramics (Buck 2019; Schmidt and Shackley 2016). The horticultural industry promotes biochar as a peat substitute (Carbon Gold 2025), and it has potential for carbon removal when combined with bioenergy capture and storage (Buck 2019).

simultaneously a place from which biochar feedstocks are supplied, e.g. in the form of biomass crops and agricultural residues, a site of biochar production (in small and larger production units), and a site of biochar application or deployment, with the latter position attracting particular attention from a range of stakeholders (Green Alliance 2022; NFU 2021; Royal Society and Royal Academy of Engineering 2018). However, to date there has been a lack of critical investigation of the connections being made between agriculture and biochar as a land-based GGR approach. The somewhat limited social science research into biochar which has explored farmer awareness and receptiveness include Clare et al. (2014), Latawiec et al. (2017) and Otte and Vik (2017). Further research is needed because like other GGR technologies, biochar is mostly promissory, being relatively new and emergent, the benefits and risks not yet fully investigated, its governance arrangements underdeveloped, and the perspectives, knowledges, and experiences of key stakeholders barely unaccounted for. For example, in their analysis of biochar in the UK print news media, Morris et al. (2024) found that reporting of biochar in agriculture was almost completely non-existent, a situation that they argued is likely to contribute to a closing down of societal debate around this technology.

In response to this research gap, this paper seeks to investigate and illuminate the various and often contested ways in which biochar in UK agriculture is envisaged and understood by a breadth of stakeholders, particularly in the context of GGR and the broader net zero agenda. Given the UK's substantial public sector investment in biochar as a component of its strategy for GGR and achieving net zero targets, this context offers an especially timely and relevant setting for our analysis. The specific lens we adopt is that of sociotechnical visions and imaginaries (Hilgartner 2015; Jasanoff and Kim 2009), a future oriented approach to exploring technologies including those like biochar which are unsettled. It is a theoretical lens which also directs analytical attention to the tensions, contestations, and negotiations between emerging visions and established imaginaries.

Net zero is conceptualised (following Jara 2025) as an established sociotechnical imaginary that provides a widely recognised and institutionally supported vision of a desirable future, in which technological innovation and new practices, including land-based GGR approaches, are seen as essential to achieving decarbonisation and long-term climate goals. For stakeholders who align themselves with this net zero imaginary, biochar is a promising means to achieve GGR and thus reinforces the dominant narrative of technological solutions to climate change. At the same time, the net zero imaginary serves as a powerful anchor and reference point against which different sociotechnical visions of biochar are shaped, debated, and defined. Understanding the

multiplicity of emerging visions of biochar in agriculture provides an opportunity for discussion about which of these emerging visions might be more achievable, just, and inclusive and how biochar might be governed in the future. The specific questions the paper seeks to answer are: What are the different sociotechnical visions of biochar in UK agriculture? Which stakeholders are these different sociotechnical visions of biochar associated with? How is the sociotechnical imaginary of net zero reinforced and / or challenged by emerging visions of biochar and with what implications for the future development of these visions?

In the following section, we discuss further the conceptual approach of sociotechnical imaginaries, paying particular attention to the net zero imaginary, and how—conceptually—emerging sociotechnical visions have been distinguished from imaginaries. We then outline how qualitative data were produced to enable us to identify different sociotechnical visions of biochar, before describing each of these visions. Finally, we discuss how the sociotechnical visions of biochar in UK agriculture are characterised by diversity and contestation, reflecting a spectrum of stakeholder perspectives and priorities, features that are often smoothed over or ignored in policy and scientific arenas. We show that the future of biochar in UK agriculture cannot be reduced to a single trajectory aligned with net zero ambitions. Instead, multiple, sometimes competing, visions coexist—some emphasising technological solutions and large-scale carbon removal, while others highlight practical on-farm benefits, business opportunities, and diverse environmental outcomes. This multiplicity necessitates a more pluralistic and inclusive approach to biochar governance, one that recognises and accommodates the varied priorities of key actors including farmers and other agricultural stakeholders. The paper also contributes to the literature on sociotechnical imaginaries and sociotechnical visions by focusing attention on grassroots sociotechnical visions articulated by farmers and other agricultural stakeholders. Historically, the study of sociotechnical imaginaries and visions has largely focused upon societal elites and institutional authorities (Christiansen and Carton 2021).

Sociotechnical imaginaries and emerging sociotechnical visions

Sociotechnical imaginaries and the net zero sociotechnical imaginary

Although our primary analytical focus is sociotechnical visions, the concept of sociotechnical imaginary provides the broader, collectively held context within which visions are articulated, contested, and potentially realised. By

situating visions within the context of imaginaries, we can better understand how new ideas and approaches—such as those related to biochar in agriculture—either align with, contest, or seek to offer alternatives to these dominant imaginaries. This relationship is critical for assessing the plausibility, inclusivity, and transformative potential of emerging visions. Analysing the interplay between visions and imaginaries allows us to explore how certain futures become seen as more legitimate or achievable than others. The broader sociotechnical imaginary of net zero, which emphasises technological solutions to climate change and is embedded in policy, legislation, and sectoral commitments, has become institutionalised on an international scale (but not universally) including in the UK. This provides a powerful context within which visions for biochar are articulated and evaluated. Therefore, we discuss this in some detail after outlining the concept of sociotechnical imaginary and before moving on to discuss the distinctive concept of sociotechnical vision.

Sociotechnical imaginaries, a concept originally coined by Jasanoff and Kim (2009), has gained prominence over recent years, with scholars using this approach to study sectors such as energy (Carvalho et al. 2022; Chateau et al. 2021; Jasanoff and Simmet 2021; Longhurst and Chilvers 2019), transport (Braun and Randell 2020; Graf and Sonberger 2020; Mutter and Rohrer 2022), agriculture (Bain et al. 2020; Ruder et al. 2025; Shortall 2019) and health (Hoff 2023; Silva et al. 2022). Sociotechnical imaginaries are defined as “collectively held, institutionally stabilised, 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” (Jasanoff 2015, p. 4). Whilst the sociotechnical imaginary concept was originally concerned with the state and state actors, its application is now much wider, and considers publics, organisations, and civil society (Jasanoff and Simmet 2021; Ruder et al. 2025). As a concept, sociotechnical imaginaries comprise social norms, discourses, cultural meanings, and metaphors which focus on desirable futures, but which can also warn against risks and hazards of scientific and technological developments (Jasanoff and Kim 2009). As such, sociotechnical imaginaries pay attention to what is good for society in relation to scientific and technological developments, envisioning how these innovations can meet the needs of publics (Jasanoff and Kim 2009).

We now turn to a more detailed examination of the net zero sociotechnical imaginary, exploring its origins, defining features, and its pervasive influence on climate policy and technological development in the UK. Net zero can be understood as a sociotechnical imaginary because it is implemented and represented in government and corporate

discussions, emissions targets, energy scenarios, legislation, and scientific statements that focus on technological solutions and fossil fuel systems managed by corporations (Jara 2025). The net zero concept gained global prominence when it appeared in the Paris Agreement of 2015. In this landmark accord, countries pledged “to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century” (UNFCCC 2015). The Paris Agreement, signed by the member states of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015, aims to keep the global average temperature increase well below 2 °C, while striving to limit the rise to 1.5 °C (Anderson and Peters 2016). Achieving these targets necessitates rapid and substantial reductions in emissions in the short term, complemented by collective, long-term measures such as carbon removal to maximise impact (Rockström et al. 2017).

Momentum for net zero targets is building globally. In 2017, Sweden became the first country to set a net zero goal in law, targeting 2045. China, the world’s largest emitter of greenhouse gases, has pledged to achieve carbon neutrality before 2060 (Energy and Climate Intelligence Unit 2023). Alongside these international developments, the UK had already passed the Climate Change Act in 2008 and was the first nation to implement a long-term, legally binding framework aimed at reducing carbon emissions (Climate Change Committee 2025). However, this act was made more ambitious in 2019 when the commitment to net zero by 2050 was made, with the UK becoming the first G7 nation to do so (LSE and the Grantham Research Institute on Climate Change and the Environment 2020). This bold, national commitment, underscores the importance of action at all levels of government including local authorities, one of the smallest scales of government in the UK and seen as key by the Climate Change Committee (2020) and the Skidmore Review (Skidmore 2022) in addressing climate change. Whilst there is no statutory responsibility for them to do so (Garvey et al. 2025), 73% of local authorities are committed to net zero emissions in their jurisdiction (National Audit Office 2021). For example, Nottingham City Council (2025) is aiming to be the first carbon neutral city in the UK by 2028. This local level ambition is mirrored by similar commitments across different sectors and industries in the UK, demonstrating a coordinated effort towards achieving net zero goals. The National Farmers Union (NFU) has set a goal for the entire agricultural sector to reach net zero by 2040 (NFU 2021). To facilitate progress toward net zero, some businesses are engaging with carbon markets, which have emerged as a crucial mechanism for achieving these targets. HSBC (2022) contends that the voluntary carbon market, when used as a complement to – rather than a

substitute for – the decarbonisation of a company’s operations, could serve as a valuable tool for accelerating action on climate change.

There are two main types of carbon markets: compliance markets, which are regulated by governments and typically form part of national or regional emissions trading schemes, and voluntary markets, where companies and individuals can purchase credits to offset their carbon footprint outside of regulatory requirements (Osborne and Shapiro-Garza 2018). The growth of carbon markets has been accompanied by debates over their effectiveness and integrity. Critics argue that poorly regulated markets risk allowing companies to continue polluting while buying inexpensive credits that may not represent genuine emissions reductions (Nawaz et al. 2025; Price et al. 2024). Proponents, however, highlight that robust standards, transparency, and independent verification can help ensure that carbon markets contribute meaningfully to global climate goals (Kreibich 2024). As net zero ambitions intensify, the role of carbon markets as a tool for emissions mitigation and as a source of funding for innovative carbon removal technologies will likely become increasingly significant in the years ahead (Deknatel and van der Loos 2025; Kreibich 2024). The expanding landscape of climate commitments and the growing drive towards net zero signifies a fundamental shift for climate policy and action at every level of society.

Having established the significance of sociotechnical imaginaries and examined the net zero imaginary in detail, we now shift our focus to the concept of sociotechnical visions. These visions are active constituents in the ongoing evolution of sociotechnical futures.

Sociotechnical visions

Research on sociotechnical visions is emergent relative to imaginaries and seeks to distinguish sociotechnical vision(s) from sociotechnical imaginary/ies where the former has yet to settle and become institutionalised. Sociotechnical visions are particularly relevant when it comes to investigating debates about new technologies by different stakeholder groups. These stakeholder groups can be seen as sociotechnical vanguards who are described by Hilgartner (2015, p. 34) as “relatively small collectives that formulate and act intentionally to realize particular sociotechnical visions of the future that have yet to be accepted by wider collectives”. The sociotechnical visions put forward by these groups can be numerous and fleeting compared to the stability and longer history of sociotechnical imaginaries. Different sociotechnical visions can align, interact, and conflict with one another (Christiansen and Carton 2021) and with established sociotechnical imaginaries (Polzin 2024). As Hilgartner (2015, p. 35) alludes to, sociotechnical vanguards

“do not just articulate visions but they also take action on the ground ... to prototype, build and configure practices that should – literally – realize their ideas”. By putting their ideas into practice, sociotechnical vanguards can potentially challenge established sociotechnical imaginaries.

Although sociotechnical visions have the capability to inspire, they are often grounded in familiar experiences to ensure they are taken seriously and are not viewed as fanciful or outlandish (Hilgartner 2015). For example, the sociotechnical visions around synthetic biology draw on sociotechnical imaginaries associated with the importance of innovation and the computer revolution (Hilgartner 2015), whilst the sociotechnical visions associated with negative emission technologies in Sweden connect to the country’s identity as an international leader in addressing climate change (Christiansen and Carton 2021). In this study, Christiansen and Carton (2021) identified several distinct negative emission visions, each varying in their level of contestation and degree of institutionalisation. They found there was broad consensus regarding the preferred role of bioenergy with carbon capture and storage (BECCS) within Swedish energy systems, whereas interventions in the land-use sector were subject to greater dispute. These variations were suggested as being linked to existing bioeconomy imaginaries in Sweden, where energy systems were predominantly geared towards bioenergy use, as well as to underlying political and economic interests.

Studies investigating sociotechnical visions have examined solar geoengineering (Flegal and Gupta 2018), negative emission technologies (Christiansen and Carton 2021), neurotech (Knopf et al. 2023), urban wind power (Lunovich and Kloppenburg 2023), smart homes (Rohde and Santarius 2023), agricultural transformation in Germany (Polzin 2024), the bio-based construction sector (Fischer and Losacker 2025) and vertical farming (Gugganig 2025). Whilst there is a breadth to the technologies investigated, all these studies share a common interest in the arguments made for competing sociotechnical visions by key stakeholders, the so-called sociotechnical vanguards, and how these arguments shape debates about desirable futures. In the case under examination, it is the sociotechnical visions of biochar in agriculture articulated by a variety of stakeholder vanguards that is of interest.

By situating our study within the context of UK agriculture—where biochar is still an emerging and promissory technology—we contribute to the literature on sociotechnical imaginaries and sociotechnical visions by directing attention to the grassroots sociotechnical visions articulated by farmers and other agricultural stakeholders. Traditionally, sociotechnical imaginaries and visions have been predominantly shaped by societal elites and institutional authorities, a tendency reflected in academic research that

frequently neglects the perspectives and experiences of those at the grassroots (Christiansen and Carton 2021). In the following section, we turn our attention to the methods employed to identify these visions, outlining the research design, data collection strategies, and analytical approach that underpin our findings.

Methods

To obtain detailed insights into the sociotechnical visions of biochar and the values, assumptions, and contestations shaping these, two types of qualitative method were adopted. Semi-structured interviews were conducted with individuals and organisations with stated interests—positive, negative, or neutral—in biochar. These stakeholders came from a range of sectors, including agricultural research and development, farming industry representatives, environmental advocacy groups, UK government agencies, local authorities, commercial and community-based biochar producers, pyrolysis machine manufacturers, forestry organisations,

were included to ensure a comprehensive range of perspectives. These interviewees were identified through various approaches:

- 1 A Google search was performed on 29 September 2021 using the terms: “biochar and UK agriculture” and “biochar and UK.”
- 2 Individuals and organisations who directly reached out following coverage in national and local media².
- 3 Additional participants were identified through stakeholder recommendations (snowball sampling).
- 4 Involvement of individuals in farm field trials³.
- 5 Identification on Twitter/X of individuals who had publicly stated their interest or involvement in biochar.

In total, 123 stakeholders with an interest or potential interest in biochar were identified. Of these, 58 (Table 1) agreed to take part in a semi-structured interview. Interviews were conducted in two distinct periods (2022 and 2023/2024) during the data collection process. Table 2 illustrates how the interviewed farmers are producing and/or using biochar.

Table 1 Types and the number of stakeholders with an actual or potential interest in biochar who were interviewed

Type of Stakeholder	Number of Stakeholders with an Actual and Potential Interest in Biochar
Farmer Focused	
Science / R & D	3
Representation / Advocacy	4
Provision of Goods and Services	1
Farmer	29
Environmental	
Advocacy	2
Government (National and Local)	
National Government	4
Local Authorities	2
Biochar Producers	
Commercial	4
Community	1
Pyrolysis Machine Manufacturer	1
Forest Focused	
Tree and Woodland Management	2
Biochar Industry Representatives	
Representation / Advocacy	3
Carbon Trading	
Carbon Trading Companies	2
TOTAL	58

industry representatives, carbon trading companies, and farmers. The study also sought input from those with potential future interest in biochar, such as owners of possible storage sites. Additionally, stakeholders from related fields, like soil carbon and other land-based GGR approaches,

² This is media coverage of the Greenhouse Gas Removal Demonstrators programme.

³ Farm field trials refer to experimental studies carried out on agricultural land owned by farmers and landowners. In the context of biochar, farm field trials involve applying biochar to selected plots and monitoring factors such as carbon storage, crop yield, and soil health over time.

Table 2 How interviewed farmers are producing and/or using biochar

Type of biochar production/use	Number of farmers
Trial farm ¹	7
Using biochar (purchased or given to them)	5
Producing their own biochar for their own use	1
Producing their own biochar for sale	3
Producing their own biochar for their own use and for sale	6
Not yet used biochar but interested	7

¹Trial farm refers to those participating in farm field trials as part of the Greenhouse Gas Removal Demonstrators programme

All interviewees were asked a wide range of questions designed to elicit their knowledge of biochar, perceptions of its potential uses, views on the associated benefits and risks, and opinions on the incentivisation and regulation of biochar. The same interview schedule was used throughout to ensure consistency and comparability across responses; however, the interviews were designed to be flexible, allowing informants to discuss their experiences and perspectives in their own words. Stakeholders were offered a choice between in-person interviews and online interviews via Microsoft Teams. However, most stakeholders, including farmers, opted for Teams due to convenience and time constraints. Interviews typically lasted around one hour each, allowing for comprehensive exploration of individual viewpoints and experiences. All interviews were audio-recorded with participants' consent and subsequently transcribed in full to ensure accuracy and depth of analysis.

Building on the understanding of how sociotechnical visions are collectively shaped and contested, as articulated in the earlier section, thematic analysis (Braun and Clarke 2006) provided a structured lens through which to systematically examine the interview transcripts to initially identify the themes that spanned our data. Initial coding focused on the themes of economics, governance and accountability, innovation, justice or morality, risk (and uncertainty), security, salvation, substitution, and tradition. These thematic categories were informed by a combination of concepts from the sociotechnical visions literature and inductive patterns that emerged during early coding. In operationalising these themes, we coded for recurring statements that signalled underlying values or assumptions—for example, references to cost or efficiency (economics), appeals to regulation or responsibility (governance and accountability), expressions of uncertainty (risk), or moral evaluations (justice/morality). Other themes, such as “salvation,” “substitution,” and “tradition,” emerged inductively as participants repeatedly invoked narratives of technological rescue, replacement, or continuity with established practices. These thematic patterns provided the analytical foundation from which we

subsequently identified expectations and arguments that cohered into broader sociotechnical visions.

These visions are not just isolated comments or ideas; rather, they are articulated through recurring language, or arguments that indicate a broader, underlying set of values, expectations, and ambitions. This approach enabled us to map the contours of the evolving discourse on biochar in UK agriculture, not only identifying instances where stakeholders align with the prevailing net zero imaginary but also surfacing voices that contest its assumptions or feasibility within the agricultural context. In doing so, we illuminate the complexities and tensions of biochar in UK agriculture, revealing a landscape where alignment with the prevailing net zero imaginary, contestation, and the offering of alternative sociotechnical visions continually shape the evolving debate.

In the presentation of interview data, interviewees are presented anonymously, using generic informant numbers (such as I3 for informant 3) while also indicating their stakeholder category (for example, farmer). Since the biochar industry in the UK is small and developing, stakeholders were assured complete anonymity. Ethical approval for the entire study was granted by The Research Ethics Panel, School of Geography, University of Nottingham, UK. All participants provided informed consent, and all data were stored securely in accordance with institutional data protection requirements.

Stakeholder interviews were supplemented with a document analysis which has been ongoing since the start of the research in 2021. We reviewed individual websites for documents or reports about biochar. These websites belonged to the organisations identified during our initial interviewee search, ensuring that the document analysis drew on the same set of relevant sectoral actors. The term “biochar” was used to search these sites, and any material referencing biochar in relation to the UK was included. We also collected documents on net zero initiatives from prominent agricultural stakeholders such as the National Farmers Union (NFU), ensuring we covered major arguments surrounding alternative land-based strategies for reducing carbon emissions recommended to stakeholders and suitable for agriculture: afforestation, peatland restoration, enhanced rock weathering, and increasing soil carbon levels. These searches yielded a range of document types, including strategy documents, research reports, guidance documents, and online information pages. Altogether, we identified 36 relevant items. A full list of these documents is provided in the online Appendix 1. This approach allowed us to incorporate major viewpoints and policy recommendations as key dimensions of the sociotechnical visions which are elucidated in the following section.

Sociotechnical visions of biochar in UK agriculture

We identify two overarching sociotechnical visions of biochar in UK agriculture. The first is a sociotechnical vision of greenhouse gas removal through biochar produced at scale and applied to agricultural land. Farmers are found to align with or contest this vision. A second sociotechnical vision of biochar for multiple on-farm benefits is identified consisting of dimension 1: biochar production for multiple farm business benefits; dimension 2: biochar use for realising agricultural production benefits; and dimension 3: biochar production and use for on-farm biodiversity benefits. In the sub-sections that follow we describe each of these visions.

A sociotechnical vision of GGR through biochar produced at scale and applied to agricultural land

The first sociotechnical vision of biochar is focused on GGR in order to address climate change. As such, the vision here is in producing biochar ‘at scale’⁴, in large industrial pyrolysis units, with carbon markets providing the vital financial mechanism to incentivise scaling up. In its 2025 document, *Biochar removes carbon*, the International Biochar Initiative (2025)⁵ sets out how biochar carbon trading works. It states that biochar producers sell carbon credits whilst also selling the biochar they produce. The carbon credits are traded through companies such as Carbon Futures and Puro.earth and are sold to companies such as Microsoft or British Airways. This vision can be understood as one actively constructed and promoted by vanguards (Hilgartner 2015) who articulate, justify, and work to materialise a future in which industrial-scale biochar production and carbon markets are tightly coupled. This coupling is presented as a coherent and desirable trajectory that these vanguards work to stabilise.

Vanguards of this sociotechnical vision include scientists and scientific organisations, biochar entrepreneurs, carbon trading companies, and some policy actors. They picture a future where biochar is produced at scale for climate mitigation purposes with this then being applied (or ‘deployed’) to agricultural land. These institutional vanguards consistently

frame this model as a credible pathway for delivering permanent carbon removal. Both the Royal Society and Royal Academy of Engineering (2018) and Green Alliance (2022) advocate for biochar application to land, whilst the NFU (2021, p. 14) state that by “early next decade, the NFU believes that land spreading of biochar could be capturing 2.5 million tonnes/year of CO₂ across the UK”. In this vision, farmland is envisaged as a spatially extensive storage site for carbon with farmers conceptualised as passive ‘recipients’ of biochar produced (for the most part) off-farm and as competent technicians (Burgess et al. 2000) in the application of biochar to their land. The expectation is that the perceived agricultural (co)benefits of biochar will encourage farmers to engage with this approach and accept the associated costs of purchasing and spreading biochar to their land. This enrolment strategy aligns with Hilgartner’s (2015) observation that vanguards often assign specific roles to downstream actors, in this case, farmers, positioning them as implementers of a future largely conceived elsewhere. Importantly, this imagined role for farmers reflects the expectations of vanguards rather than the lived realities or priorities of farmers themselves, a tension explored later in the analysis.

The origins of this sociotechnical vision appear to lie in the work of US-based soil scientist Johannes Lehmann and colleagues who first proposed biochar as an approach to carbon storage in 2006. Whilst the authors acknowledge the use of biochar as a soil conditioner, they state their “contribution restricts itself to exploring the important and so far undocumented biological feasibility and the potential quantitative importance with respect to C sequestration in soil” (Lehmann et al. 2006, p. 405). Interestingly, whilst these authors recognise that there may be a need for technology standards and incentives for the scaling up of biochar, the main mechanism for realising this vision is carbon trading. The strategy of applying biochar to soil for carbon storage with carbon trading as an approach to scaling was again proposed by Lehmann (2007) in a second journal article. Two years on, the Royal Society (2009) published its *Geoengineering the Climate* report. This report states that proponents of biochar are claiming that large amounts of carbon storage are achievable if this technology is used, quoting the figure of 5.5 to 9.5 GtC/yr by 2100 from the Lehmann et al. (2006) article. The Royal Society’s report underscores the imagined importance of carbon markets as the key mechanism to encourage the use of biochar as a land-based GGR technology.

Interviewees also described growing corporate interest in voluntary carbon markets, with a commercial biochar producer noting that: “There’s no doubt that there is interest in carbon trading and voluntary [biochar] carbon credit trading is one of these. And you see a number of companies coming

⁴ If biochar is applied at 10 tonnes per hectare, a level that a number of EU field trials suggest would not cause adverse impacts on crop yields, to all 6 M hectares of arable and temporary grassland in the UK this amounts to ca. 50 MtC in total. This represents a relatively small contribution to the 35 MtC Royal Society annual target. In England, the Environment Agency currently only allows an application rate of 1 tonne per hectare.

⁵ The International Biochar Initiative (IBI) is an international non-profit membership organisation dedicated to advancing the research and promotion of biochar. It provides a platform for fostering stakeholder collaboration, disseminating best industry practices, and upholding environmental and ethical standards to ensure that biochar systems are safe and economically sustainable.

forward using the voluntary market, but they're using it voluntarily themselves. They are not forced to do it, but they do it because it's good marketing and those are companies like Microsoft, Shopify" (I9, commercial biochar producer). A second interviewee, a carbon trading representative, stated that: "One of my main interests is being driven by wanting to try and create voluntary [biochar] carbon credits. Voluntary carbon offsets using biochar. I noted that they traded at high prices relative to other voluntary carbon offsets" (I33, carbon trading stakeholder). Taken together, these accounts illustrate how voluntary biochar carbon trading is emerging as a new opportunity and offers insights into how it might work in practice. They also show how growing corporate interest, alongside the activities of carbon-market traders, is helping to push this space forward, positioning these actors as vanguards in the development of voluntary biochar carbon markets.

The scientific claims and market developments mutually reinforce the idea that biochar is both technically viable and economically actionable, strengthening the authority of the vision. Building on this institutional framing, the science-led vision is underpinned by a shared belief that biochar's value lies in its permanence. It is permanence that allows biochar carbon credits to be traded with confidence. As a commercial biochar producer explained: "I think biochar is the most secure and durable form of carbon storage because you can literally pick it up and hold it. ... I can produce a ton of biochar today and you can hold that carbon and it's there and we're all very happy and we know it exists. So, I think it will provide the foundations for a movement towards carbon trading which is far more secure and trusted" (I17, commercial biochar producer). Such accounts reinforce the vanguard narrative that biochar offers a tangible form of carbon removal.

Consequently, this illustrates how the science-led vanguard narrative operates. Scientific projections are adopted by authoritative institutions and are used to justify the creation of new market infrastructures. Through this process, the vanguard narrative not only promotes biochar as a viable GGR technology but also narrows the field of alternative futures by presenting industrial-scale production, carbon trading, and deployment to agricultural land as the inevitable pathway. In this vision, farmers are not central decision-makers but downstream implementers whose participation is assumed to follow once the technical and economic architecture is in place.

Farmer alignment with the vision of GGR through biochar applied to agricultural land

If this particular sociotechnical vision of GGR through biochar produced at scale and applied to agricultural land is

going to become institutionally embedded, it will require widespread 'buy in' from farmers who have operational control over agricultural land. This 'buy in' represents a crucial moment in which vanguards must successfully enrol downstream actors into their imagined future. Without such enrolment, the sociotechnical vision cannot stabilise or scale. Our data revealed some evidence of this alignment, but it was limited. For example, several farmers and other agricultural stakeholders recognised that biochar could be used to capture carbon thus preventing it being returned to the atmosphere.

Additionally, agriculture was imagined by farmers as the only industry sector capable of storing carbon and, by extension, agricultural land was envisioned as a key deployment site for biochar. As a farmer explained: "You can have electric cars, but farming is the only one that can really take down the carbon. It's the only one that can put it in the soil and if you're using biochar, it can keep it there" (I52, livestock farmer, international, producing their own biochar for their own use). The farmer recognises that soil acts as a storage vessel for the carbon locked up in biochar, thus aligning themselves with the vision of GGR through biochar applied to agricultural land. This quote illustrates how vanguard framings circulate and are taken up by some farmers, who reproduce the narrative of soil as a long-term carbon storage site. Nevertheless, many farmers and other agricultural stakeholders imagine that financial incentives will be necessary to realise this vision, particularly given the costs associated with spreading biochar. The following quote illustrates this position: "If there's a shortfall in terms of the economic benefits [of biochar] to the farm business, then there needs to be economic payments. There needs to be payments to farmers to justify that" (I1, Farmer Focused Science / R & D stakeholder). While farmers may accept aspects of the vision, they resist assuming the financial burden of implementing it. This reflects Hilgartner's (2015) point that vanguards must negotiate with, rather than simply dictate to, those they seek to enrol.

It was (national) governments that were envisaged as the most likely source of biochar use payments or incentives, as part of the wider move, post Brexit, in UK agricultural policy of 'payments for public goods'. The UK Government's Environmental Land Management schemes (ELMs) (Department for Environment, Food and Rural Affairs 2023) were imagined as a potential mechanism to incentivise biochar use, with one farmer emphatically clear about this potential: "I mean, let's say if you committed to putting in [to ELMs] a number of hectares, spreading X number of tonnes [of biochar] over X number of hectares every year over a 5-year period and you got paid accordingly, I would say yes" (I41, livestock farmer, England, trial farm). Farmers see government incentives as a necessary condition for

participating in the vision, indicating that the alignment sought by vanguards is contingent on public funding.

Although these farmers and other agricultural stakeholders demonstrate some alignment with the sociotechnical vision of biochar for carbon storage on agricultural land, they were much more likely to question, resist and contest this vision in various ways posing not insignificant challenges to the vision's vanguards. In doing so, they mobilised arguments relating to the economics, injustices, and risks of biochar. It is to this contestation and resistance that the discussion now turns.

Farmers contesting the vision of GGR through biochar applied to agricultural land

The first area of resistance amongst farmers and other agricultural stakeholders focused on the economic viability of earmarking agricultural land as a key deployment site for biochar. Even when farmers and other agricultural stakeholders recognised a range of actual and potential benefits of biochar, many emphasised that the costs of purchasing biochar are prohibitively high, perceiving this to be due to limited supply. The absence of unequivocal agricultural benefits from biochar deployment, e.g. as a credible nitrogen fertiliser substitute, and the inability of farmers to claim carbon credits on bought-in biochar represent significant financial barriers for farmers to engage with the vision at current biochar prices. One farmer explained that whilst biochar is “very good at storing carbon ... financially it doesn't work” (I57, livestock farmer, Wales, producing their own biochar for their own use and for sale), and another elaborated that “[farmers] ... are quite short-term thinking and they won't be incentivised to pay for biochar to apply to their land unless they see an immediate impact on yields which it is unlikely to do” (I50, livestock farmer, England, using biochar [purchased or given to them]). These concerns illustrate how farmers being enrolled into the science-led vision evaluate it through the lens of farm-level economic realities. This reveals a gap between the promissory claims advanced by the vanguards promoting the vision and the practical constraints experienced by those expected to implement it.

It was widely but not universally recognised amongst interviewees that carbon credits linked to biochar would be realised by the off-farm producers of biochar and not by the farmers applying the biochar to land. As one farmer explained: “The only time they [a farmer] will be able to claim for carbon sequestration is if they own the pyrolysis unit. If they're purchasing biochar from somewhere else ... they'll [carbon credits] be sold to somebody else” (I50, livestock farmer, England, using biochar [purchased or given to them]). This situation, several interviewees claimed, is a powerful financial disincentive to biochar deployment,

and highlights a key misalignment within the science-led sociotechnical vision that imagines carbon markets as the primary mechanism for driving uptake. For many farmers, this misalignment was a key reason for questioning the practicality and fairness of the science-led vision.

Taken together, these dynamics point to a broader distributive injustice concern embedded in the science-led sociotechnical vision that imagines carbon markets as central to scaling up biochar production and deployment to farmland. In this vision, the ‘winners’ are off-farm biochar producers who can sell the carbon credits, while the ‘losers’ are farmers who apply the biochar but receive neither the credits nor any demonstrated agricultural co-benefits, which are as yet unproven. In short, farmers and other agricultural stakeholders argued that in the absence of a meaningful monetary benefit, either in the form of carbon credits, and / or reduced input costs, and / or increased yields, they would be unlikely to buy into this vision, particularly at current costs. This imbalance challenges the science-led vision by exposing how its economic architecture privileges off-farm actors. The efforts of the vanguards promoting this vision are weakened as the envisioned benefits do not align with farmers' interests.

The risks surrounding the application of (off-farm produced) biochar to agricultural land represent another way in which farmers and other agricultural stakeholders questioned and contested this sociotechnical vision. A key area of risk is encapsulated in the statement, “you don't want to be causing damage to the soil” (I28, arable farmer, England, not yet used biochar but interested) as a result of biochar made from contaminated feedstocks. Various farmers and other agricultural stakeholders reflected on this risk, citing particular concerns with biochar made from local authority waste, sewage sludge, domestic food waste, and treated wood. However, in most cases it was acknowledged that the potential risk to soils from contaminated biochar could be avoided through the development of effective regulation of feedstocks so that farmers could be confident about the biochar they are buying and using⁶. These concerns highlight how farmers scrutinise the assumptions embedded in the science-led vision, particularly around technological reliability, and regulatory readiness. Their caution illustrates that enrolment is dependent on assurances that the envisioned future will not compromise soil health or farm viability.

Distinct from the risks arising from feedstock composition is biochar's potential to ‘lock up nutrients’, as well as pesticides and herbicides when applied to soil. This may have negative implications for crop health, as explained

⁶ The use or UK specific development of the European Biochar Certificate was discussed by some farmers as an acceptable approach to regulating biochar quality and safety.

by one of the farmers who identified this risk: “I guess one thing might be the lock up of pre-emergent herbicides, either reducing their efficacy or potentially having longer toxicity in the soil than you would normally expect, so potentially having negative effects at a later date” (I35, mixed farmer, England, not yet used biochar but interested). This was also alluded to by a Farmer Focused Representation / Advocacy stakeholder (I3) who stated that “if we are applying a product that could potentially lock up nutrients, then ... we need to think a bit more about where this biochar ends up.” Such concerns challenge the vision by introducing uncertainty about the broader agronomic impacts of biochar. Farmers introduce friction, thereby complicating the promissory narrative advanced by its proponents.

Although the main risks of biochar focused on the application of biochar to agricultural land, also identified and a cause of concern is a potential risk to the climate arising from the production of biochar, specifically, that the transportation and burning of biomass could increase GHG emissions that would not be offset by the production of biochar. This could potentially undermine the climate benefits central to the vision. As one farmer stated: “You have to be really efficient and consider how close you put your pyrolysis unit to your feedstock because otherwise the carbon and the financial benefits are reduced significantly” (I50, livestock farmer, England, using biochar [purchased or given to them]). As this farmer explains, a mitigation for the climate risk from biochar is to use locally produced feedstocks and to focus on use of agricultural and forestry residues and wastes rather than making biochar from virgin wood. It is a mitigation that points towards an alternative sociotechnical vision of biochar described in the next section.

A sociotechnical vision of biochar for multiple on-farm benefits

This alternative sociotechnical vision is fundamentally distinct in several respects from the scientifically grounded sociotechnical vision of GGR through biochar produced at scale and applied to agricultural land. At its core, it is a ‘farmer-led’ vision. Rather than being seen as passive recipients of biochar produced mostly off-farm, farmers are envisioned as active participants in both the *production* and *use* of biochar. In this vision, biochar is produced on-farm, as well as by non-farm biochar manufacturers using feedstocks supplied by farms. This sociotechnical vision grants farmers a much greater degree of power and control over biochar production and use and is also championed by other agricultural stakeholders. Additionally, in contrast with the first vision, there is a greater degree of financial optimism and optimism about biochar’s agricultural but also on-farm environmental benefits among both farmers

and other agricultural stakeholders. Crucially, this vision shifts the emphasis away from GGR and carbon storage. Instead, it highlights a range of other potential on-farm advantages offered by biochar, such as improved soil quality and increased farm income. This shift marks a significant reorientation: farmers are no longer actors to be enrolled into a vision but instead emerge as vanguards articulating and advancing their own sociotechnical future. They are actively constructing an alternative sociotechnical vision grounded in farm level priorities and opportunities.

Several dimensions to this farmer-led vision of biochar can be identified each with a slightly different emphasis and orientation to biochar production and / or use. Any given farmer or other agricultural stakeholder may align with one or more dimensions, depending on how they envisage biochar’s potential benefits on farms.

Dimension 1: biochar production for multiple farm business benefits

This dimension emphasises biochar *production* either on-farm or through localised arrangements in which farmers supply feedstocks from farms to local off-farm biochar manufacturers, including local authorities,⁷—some of whom are emerging as vanguards in the wider development of biochar systems. This vision anticipates that farmers will invest either as individuals, or as collectives / clusters to jointly own a pyrolysis unit, and thus realise biochar production on farm, granting them “as much control over that process as possible” (I37, livestock farmer, England, not yet used biochar but interested). Within this vision, one farmer has already invested in a £2.5 million biochar production unit and is confident on his returns from this investment. Such investments are very substantial and so a small number of farmers identified that they would likely require financial support (including from the public purse) to enable them to invest, either as an individual or collective, in a biochar production unit. Farmers act as vanguards by mobilising resources and experimenting with new production infrastructures. Their actions demonstrate the proactive, future-making work characteristic of vanguard activity.

Within this dimension of the farmer-led sociotechnical vision, biochar production is typically envisaged as a form of farm diversification, generating alternative income streams that can be particularly useful in helping to sustain small, family farms. The dimension imagines income derived either from the sale of on-farm produced biochar to gardeners for whom biochar is an already familiar soil amendment and to farmers and growers (currently less familiar with biochar), and / or from the sale of biochar carbon credits to a range

⁷ Local authorities are increasingly involved in biochar to enable them to meet their net zero targets.

of off-farm organisations both within the agri-food supply chain and beyond. One farmer, for example, is selling carbon credits from his farm produced biochar to Microsoft for many tens of thousands of pounds a year while another, with a newly installed biochar pyrolysis unit, concurred asserting that locally sourced feedstocks for on-farm produced biochar will lead to “a very high multiple on your carbon credit. This is going to be huge value to farmers. I think this is key to it” (I34, mixed farmer, England, producing their own biochar for sale). The financial potential from the sale of carbon credits from farm produced biochar was further described by a farmer: “Biochar certificates are going for £200, £300 a tonne in comparison to afforestation credits which are going for like £20 or £30 a tonne. The difference between the two is that afforestation is both much less permanent and takes a lot longer than biochar” (I50, livestock farmer, England, using biochar [purchased or given to them]). Farmers are actively promoting new economic models around biochar, reinforcing their role as vanguards, and shaping an alternative future in which biochar supports diversified, resilient farm businesses.

The dimension also incorporates the notion that additional farm income can be derived from selling on-farm sourced feedstocks to off-farm biochar manufacturers. ‘Waste’⁸ materials are seen as having particular potential in this process. In one case, a farmer valorised upland grasses as a biochar feedstock, following removal as a condition of his environmental management scheme agreement. He explained that “if I can convert that to a high value product [biochar] to sell on to gardeners, it has an income from the other side of it” (I57, livestock farmer, Wales, producing their own biochar for their own use and for sale). This process as imagined within the dimension adds economic value to what would otherwise be considered waste. As a Farmer Focused Science / R & D stakeholder (I4) put it: “Woodland and hedges all need a degree of management. They can be a source.” If an economic value is put on to wastes through their use in biochar production, there is likely to be better management. For woodland and hedgerow management, this has a two-fold benefit. Firstly, for farmers through income, and secondly, for biodiversity (explained below through Dimension 3). This rethinking of residues and wastes demonstrates how farmers, as vanguards, reconfigure existing materials and practices into new sociotechnical possibilities, expanding the imagined value of biochar beyond carbon storage.

By using agricultural residues and biomass from hedgerows and woodlands, farmers are empowered within this dimension to supply feedstocks specifically for local biochar

production. The dimension thus holds the promise of a more equitable distribution of biochar’s benefits, ensuring control remains local and distributive injustices are avoided, in contrast to centralised systems. As one farmer explained: “If it is community based or a cooperative, that would be a good way of doing it *because the benefits don’t just fall to one person*” (I15, landowner, England, producing their own biochar for sale). This emphasis on local control and equitable benefit-sharing reflects an effort by farmer vanguards to construct a sociotechnical future that addresses the perceived distributive injustices in the science-led vision.

Perhaps because this sociotechnical vision is farmer-led there was less evidence of contestation than was the case with the first sociotechnical vision. Nevertheless, this *was* present in relation to carbon credits from farm produced biochar. While the farm business benefits of capitalising on carbon markets excited some farmers, others (including other agricultural stakeholders) contested this when they raised fundamental, ethical concerns about biochar carbon markets. One farmer articulated this as follows: “my thoughts, overwhelmingly, is that ... [carbon trading is] pretty dodgy and untrustworthy. ... I guess it’s just like anything where there’s money to be made. There are loopholes and it’s just not robust” (I43, smallholder, international, producing their own biochar for their own use and for sale). The objection here, at least in part, relates to a perceived ineffectiveness of carbon markets more generally which made this farmer cautious of their specific application to biochar. Others talked about the undesirability of selling farm-produced biochar carbon credits to large, polluting companies as this was seen as enabling them to carry on with ‘business as usual’ when, in the opinion of these farmers, they should instead be working to reduce their carbon emissions: “I’m not sure I would trade [carbon] with, say, Virgin Airlines, and this is just using them as an example. They need to clean their own act up” (I54, arable farmer, England, trial farm). Of the same opinion was a Farmer Focused Representation / Advocacy stakeholder (I3), who stated: “I think it’s been [carbon trading] a little bit hijacked by large businesses that claim green credentials.” These ethical objections highlight that farmers are not a homogenous group; even within a farmer-led vanguard vision, alignment is not automatic. Farmers actively negotiate the moral boundaries of the future they are constructing, demonstrating that vanguard visions are themselves sites of internal contestation.

This resistance within the dimension reflects a deeper, distributive injustice concern that the agricultural sector (cf. individual farm businesses) could lose out to other industries when selling carbon credits from on-farm produced biochar, as expressed in this farmer’s question: “How can agriculture be carbon neutral if we sell all our carbon to the oil industry, for example?” (I37, livestock farmer, England,

⁸ Waste is a problematic term for some, as in the quote: “I don’t like the word waste anymore” (I34, mixed farmer, England, producing their own biochar for sale).

not yet used biochar but interested). He went on to suggest that a way of avoiding this is for biochar carbon credits produced on farm to be kept within the wider agricultural industry or supply chain, “really Arla⁹ should be buying all our carbon from us” (I37, livestock farmer, England, not yet used biochar but interested). These concerns highlight how farmer-vanguards articulate not only economic futures but also ethical and sectoral boundaries, seeking to ensure that the benefits of biochar remain within agriculture rather than flowing to external industries. In short, the immediate financial benefits to individual farm businesses of selling carbon credits raise a number of ethical questions that may dissuade some farmers from aligning with this dimension of the farmer-led vision of biochar as well as the science-led vision of biochar for GGR in which carbon markets feature as a key mechanism for ‘scaling up’.

Dimension 2: biochar use for realising agricultural production benefits

In contrast to the first dimension, the second and third dimensions of the farmer-led sociotechnical vision, envisage farmers being actively involved with biochar mostly through its *use* rather than its production. Within this second dimension, it is anticipated that farmers will purchase biochar from producers, and use it to realise various agricultural production benefits, both crop and livestock, with soil health particularly prominent amongst these anticipated benefits. Farmers act as vanguards not through technological production but through broadening the imagined uses of biochar. Their role centres on defining what counts as valuable, feasible, and desirable within farming systems.

There was a high degree of optimism among the farmer vanguards of this dimension regarding the use of biochar for soil health and its potential to increase the resilience of farm businesses. As one Farmer Focused Science / R & D stakeholder (I4) commented: “It [biochar] has that effect in the soil and anything that helps soil structure, soil health ... for what we want in the soil, as opposed to what we don’t want in the soil.” The benefits referenced by farmers and other agricultural stakeholder vanguards within this dimension included improved soil structure, greater resilience of soils to extreme weather events, increased nutrient holding capacity, and enhanced water retention. Farmers expressed their willingness to apply biochar if there were improvements to soil. As one farmer explains: “If I knew it [biochar] was going to improve the health of my soil over a period, I would be more interested than if someone said it is going to lock up lots of carbon” (I37, livestock farmer, England, not yet used biochar but interested). By emphasising soil

health, the vanguards within this dimension reframe the imagined purpose of biochar around agronomic resilience and the practical needs of their own farm systems, rather than carbon storage.

Farmers were able to discuss the perceived benefits of biochar at the general level of soil health and in greater detail. One farmer explained the science of positively and negatively charged atoms: “carbon is positive and the two bits that do a lot of leaching which is nitrate and P205. Both are negatively charged so they will be attracted to the positively charged carbon atoms within that mix and then the plants will take it all back again as you go through the growing year” (I54, arable farmer, England, trial farm). A second farmer also saw the potential benefit of biochar improving nutrient uptake by crops: “getting the biochar down as a humate ... the more carbon, the more organic matter I’ve got in the soil, the faster that soil cycle operates” (I56, arable farmer, England, using biochar [purchased or given to them]). This illustrates that farmers are not merely passive adopters of biochar but are actively engaging with and interpreting the science to assess practical benefits for their agricultural systems. Their ability to discuss biochar at both a practical and a scientific level underscores the importance of farmer expertise and experiential knowledge in evaluating and integrating biochar into farming practices.

Such interpretive work is characteristic of vanguard activity: farmers translate scientific concepts into situated, practice-based understandings shaped by their lived realities and aspirations. Their practical and experiential knowledge plays a pivotal role in this dimension of the farmer-led biochar vision, enabling them to recognise biochar’s potential for addressing agricultural production challenges and to imagine it not merely as a carbon storage technology, but as a tool for farm resilience and sustainable agricultural futures.

Dimension 3: biochar production and use for on-farm biodiversity benefits

The least well-developed dimension of the farmer-led sociotechnical vision of biochar is distinct from the previous two and therefore deserves separate attention. This third dimension focuses on the imagined biodiversity benefits that can arise from the management of hedgerows and woodland for biochar feedstocks (i.e. biochar production), along with the benefits to ‘below the ground’ biodiversity once biochar is applied to soil (i.e. biochar use).

The potential for increasing biodiversity by better managing hedgerows and woodland for biochar feedstocks (utilised in on-farm biochar production or supplied to off-farm biochar manufacturers) was widely acknowledged by interviewees. Within this dimension, different management

⁹ Arla is a dairy company and producer of dairy products in the UK.

regimes for hedgerow management such as coppicing every ten or twenty years instead of trimming every year or every third year were suggested. As one farmer explained: “what I’m saying is we can produce masses of biochar from expanding the width of hedgerows and poor areas of farms, which is what we’ve done to our farm. We’ve actually increased the wildlife corridors” (I11, livestock farmer, Wales, producing their own biochar for their own use and for sale). Farmers act as vanguards within this dimension of the farmer-led vision by reframing hedgerows and woodland as ecological assets whose value extends beyond biomass supply to the enhancement of on-farm biodiversity.

Biochar was also envisioned as beneficial for ‘below the ground’ biodiversity when added to soil. Although ultimately, the primary interest here among farmers and other agricultural stakeholders is improving soils for increased crop yields, some did recognise there was a notable co-benefit for biodiversity. One farmer said, “it [biochar] improves the soil food web basically” (I50, livestock farmer, England, using biochar [purchased or given to them]), whilst a Farmer Focused Science / R & D stakeholder (I4) explained that the “fact it [biochar] can provide a haven for fungi and bacteria in mycorrhizal fungi, and the like is useful within the soil.” Others reflected on the imagined impact on biodiversity and expanded on why it could be beneficial: “it’s a simple idea that the creepy crawlies and the bio-matter in compost could find biochar as the hotel of their dreams to put it crudely” (I40, arable and horticulture farmer, England, trial farm). These accounts illustrate how farmers extend this dimension of the farmer-led vision into the subterranean realm by constructing narratives of soil life that position biochar as part of a more biodiverse and ecologically active farm system.

Essentially, within this dimension, biochar provides a habitat and a space for microbes and soil invertebrates. Given that farmers are now being paid to deliver environmental benefits through agricultural policy, this dimension positions biochar as a potential tool for biodiversity as one farmer explained: “We can clearly demonstrate the benefits for soil [from biochar], and also the soil microbes, the biodiversity, the worms. ... We can communicate that to the public, to policymakers and to markets and demonstrate the role farming can play in delivering solutions that tackle wider society problems” (I48, arable farmer, England, not yet used biochar but interested). By linking these ecological possibilities to wider environmental goals, farmers position themselves as vanguards who situate biochar within agendas of environmental stewardship and biodiversity enhancement. Although the immediate impact of biochar use is envisaged as on-farm, the wider benefits for farmers, farming and society more broadly, are also anticipated and seen as a good news story for farming to tell.

It is evident that the farmer-led vision for biochar production and use in UK agriculture differs significantly from the science-led vision of biochar as a GGR technology. While this latter vision emphasises carbon storage, in the farmer-led vision, practical on-farm benefits, including soil health, and environmental stewardship are prioritised. Although farmer-led, the second vision is not shaped by farmers alone; local authorities and agricultural stakeholders also contribute to the development of this alternative vision and its different dimensions. The implications of this important distinction between the science-led vision and the farmer-led vision, including the various dimensions of the latter, for the future of biochar in agriculture are examined in greater depth in the following section.

Discussion

In this penultimate section, we bring together our main findings on the different sociotechnical visions of biochar in agriculture and explore how these visions align with, contest, and offer alternatives to the prevailing net zero sociotechnical imaginary. We explain the potential for each vision to gain traction but also the likely future prospects for biochar and its governance in UK agriculture.

Before turning to the implications of these findings, it is important to acknowledge the scope of the study. The empirical material was gathered at a time when the governance of carbon removal in the UK was relatively undeveloped, and the visions discussed here reflect that moment. Since then, policy discussions around carbon removal have begun to develop, and future research will be needed to examine how such changes shape the sociotechnical visions explored in this paper. While the study provides detailed insight into how different visions of biochar are articulated, it offers limited insight into how these visions are negotiated collectively. Deliberative or focus group-based approaches could therefore deepen understanding of how shared narratives and disagreements emerge in practice.

The paper contributes to the literature on sociotechnical imaginaries and sociotechnical visions by foregrounding the dynamic interplay and negotiation between top-down institutional imaginaries—such as net zero—and emergent, grassroots visions. This stands in contrast to sociotechnical imaginaries and visions that have largely been crafted by societal elites and institutional authorities, a pattern evident in academic literature where the views and lived experiences of grassroots actors are often overlooked (Christiansen and Carton 2021). Rather than treating sociotechnical imaginaries as monolithic or solely shaped by policy and scientific elites, the paper illustrates how multiple, sometimes conflicting visions can co-exist, interact, contest, and

even challenge a dominant imaginary. Importantly, sociotechnical visions are not merely reflections of prevailing imaginaries, but can actively reframe, contest, and even reshape them from the ground up. By identifying institutional actors, alongside a variety of farmers and agricultural stakeholders as sociotechnical vanguards, the paper shows how a wide range of groups imagine alternative futures, assert ethical, distributive, and place-based priorities, and work to develop, materialise, and legitimise their preferred futures for biochar. In doing so, it offers a more nuanced account of how sociotechnical change, co-production, and governance unfold.

Within the net zero imaginary, technological innovation and carbon removal strategies are foregrounded as principal routes to achieving the ambitious targets of limiting global temperature rises. The net zero imaginary thus acts as a powerful organising principle, both enabling and constraining the types of solutions that are considered legitimate and feasible for addressing climate change. In agriculture, the net zero imaginary provides a context in which land-based GGR solutions, such as biochar, are positioned as key contributors to climate mitigation. This imaginary is not neutral; it is embedded in policy, institutional narratives, and market mechanisms that valorise technological fixes and measurable carbon outcomes. The visions of biochar in agriculture can be understood as responses to the overarching net zero imaginary, but they also reveal fault lines, sites of contestation, and alternatives. These responses reflect the actions of the different sociotechnical vanguards who mobilise or resist the net zero imaginary, shaping in different ways the emerging sociotechnical landscape of biochar.

The first sociotechnical vision of biochar, which is grounded in scientific expertise and prioritises GGR at scale, aligns closely with the net zero imaginary. Here, biochar is conceptualised primarily as a technology for carbon storage, with its production and deployment designed to generate tradable carbon credits and contribute to national and corporate emissions targets. This vision is underpinned by concepts of scalability, standardisation, and market integration – core elements of the net zero imaginary. Scientists, scientific organisations, biochar entrepreneurs, carbon trading companies, and certain policy actors, act as vanguards, advancing the notion that agricultural land can serve as a vast carbon sink, and that farmers, as land managers, are essential but largely passive implementers of this agenda. These institutional sociotechnical vanguards not only articulate a carbon-centric future but are actively working to materialise it through industrial-scale pyrolysis projects, the construction of carbon market infrastructures, and certification schemes. Whilst there was some evidence of alignment within this sociotechnical vision by farmers, overall, this vision has encountered resistance from farmers, who point

to economic barriers, distributive injustices, and risks associated with biochar application. These challenges highlight the limitations of a top-down, technocratic approach and suggest that the net zero imaginary, when operationalised in this way, may struggle to secure legitimacy and widespread buy-in at the grassroots level.

In contrast, the farmer-led sociotechnical vision of biochar is less tightly coupled to the net zero imaginary and actively offers an alternative. Farmers can be understood as sociotechnical vanguards, experimenting with pyrolysis units and using biochar in diverse agricultural contexts. In doing so, they promote alternative sociotechnical futures which are grounded in everyday agricultural realities, and which emphasise on-farm benefits, business diversification, soil health, and biodiversity alongside, or even above, carbon storage. While some dimensions of the farmer-led vision (such as the sale of carbon credits from on-farm produced biochar) intersect with the net zero imaginary, there is also notable scepticism and ethical concern regarding carbon markets and their wider societal implications. Farmers and other agricultural stakeholders express discomfort with the idea of enabling other sectors to ‘offset’ their emissions rather than reducing them, and some advocate for keeping the benefits of carbon storage within the agricultural sector itself. This reflects a desire for distributive justice and a more holistic approach to sustainability, in which climate action is integrated with other agricultural and rural priorities. In doing so, the farmer-led vision and its dimensions articulate alternatives to the net zero imaginary, prioritising local economic benefits and environmental stewardship.

Some farmers and other agricultural stakeholders recognised that biochar could contribute to greenhouse gas removal, indicating a partial alignment with the science-led vision. However, this alignment was limited and generally secondary to concerns about soil health, farm business resilience, and biodiversity. These overlaps—both within the farmer-led dimensions and, to a limited extent, across the farmer-led and science-led visions—reflect how practical considerations shape farmers’ and other agricultural stakeholders’ engagement with biochar’s potential. On the other hand, institutional vanguards associated with the science-led vision—including scientists, scientific organisations, biochar entrepreneurs, carbon trading companies, and certain policy actors—did not express such blending. Instead, they focused on the science-led sociotechnical vision, with its focus on carbon removal and storage for climate mitigation.

The net zero sociotechnical imaginary acts as both an enabler and a site of contestation for different visions of biochar in agriculture. The science-led vision draws legitimacy from net zero’s institutional authority, but risks alienating key stakeholders by marginalising their concerns and expertise. The farmer-led vision, meanwhile, seeks to broaden the

debate and reframe the purposes and potential of biochar, advocating for solutions that are locally grounded, socially just, and environmentally beneficial beyond carbon metrics. These dynamics highlight how the different vanguards mobilise the competing visions. The existence of the science-led and farmer-led sociotechnical visions suggests that the future of biochar in UK agriculture – and its contribution to net zero – will depend on ongoing negotiation and the capacity to reconcile divergent priorities. If the science-led vision of biochar in agriculture remains narrowly defined and aligned only to carbon and the net zero imaginary, it may foreclose alternative pathways and fail to address underlying issues of equity, knowledge, and rural livelihoods. Conversely, the more open and inclusive approaches of the farmer-led vision of biochar in agriculture could support a richer, more robust debate and help shape governance arrangements that are both effective and legitimate. Understanding and engaging with the alignments, contestations, and alternatives between the net zero imaginary and the emerging sociotechnical visions of biochar in agriculture is therefore essential for fostering more democratic and equitable approaches to biochar implementation within the agricultural sector. These dynamics also raise questions about whether the patterns identified in the UK reflect broader international trends or more locally specific configurations.

There is scope for comparative research to examine how sociotechnical visions of biochar emerge in different agricultural contexts. Existing studies already show that biochar is taken up in diverse ways internationally. In Brazil, for example, scientific actors dominate emerging networks and frame biochar primarily around soil fertility and residue management rather than carbon removal (Rittl et al. 2015). Research with farmers in Poland similarly highlights how biochar use is shaped by perceived agronomic benefits, cost, and limited familiarity with the technology (Latawiec et al. 2017). Bringing these contrasts into dialogue with the UK case would help clarify whether the differences identified here between the science-led and farmer-led visions reflect particular features of UK agricultural systems or point to broader patterns in how sociotechnical vanguards articulate and advance competing visions of biochar's future roles. Such comparative work would help situate the UK's emerging sociotechnical visions of biochar within a wider set of international visions, clarifying how different actor configurations and priorities shape the trajectories through which biochar develops across agricultural contexts.

A further implication of our findings concerns the emerging governance frameworks shaping carbon removal activities in the UK. Carbon removal governance is currently in flux, with significant recent developments such as the European Union's (EU) Carbon Removals and Carbon Farming (CRCF) Regulation (November 2024) designed

to strengthen the integrity, transparency, and credibility of carbon markets. Although the UK is no longer part of the EU, the UK government's Department for Energy Security and Net Zero (DESNZ) has indicated an intention to align with the CRCF (Thoppil et al. 2026). This positions the CRCF as an emerging governance reference point for carbon removal efforts in the UK. In this context, the CRCF is primarily relevant to actors seeking to generate certified carbon credits, particularly biochar producers and carbon trading companies. Its emphasis on quantification, additionality, and permanence aligns closely with the science-led sociotechnical vision of biochar produced at scale and applied to agricultural land, a vision that assumes carbon markets will provide the primary incentive for such scaling. These developments illustrate how emerging governance frameworks may reinforce particular sociotechnical visions of biochar, especially those oriented toward carbon market participation, potentially narrowing the range of futures that become institutionally supported.

The ability to reconcile the divergent visions of biochar in UK agriculture through democratic processes will determine the future of biochar in UK agriculture. Recognising the presence of multiple sociotechnical vanguards is important, as each group brings different forms of expertise, authority, and practical experience. Our findings highlight the need for inclusive governance arrangements that recognise, address, and accommodate the expertise, agency, and ethical concerns of agricultural stakeholders. The farmer-led vision and its dimensions, offer contestation and alternatives to the net zero imaginary, providing pathways to more robust and legitimate biochar implementation by foregrounding local economic benefits and environmental stewardship alongside climate mitigation objectives. If these perspectives are sidelined, there is a risk that biochar policy and practice will lack legitimacy, fail to address rural priorities, and ultimately overlook the aspirations of agricultural stakeholders including farmers.

Within UK agricultural governance, the science-led vision and the farmer-led vision identified in this research suggest that effective governance will need to accommodate the different priorities of biochar use. For institutional actors, biochar is primarily framed as a greenhouse gas removal technology, whereas farmers and other agricultural stakeholders emphasise soil health, farm business resilience, and biodiversity benefits. In practical terms, pluralistic governance could build on existing UK policy frameworks while addressing current gaps. DESNZ's emerging work on non-carbon capture and storage (CCS) reliant greenhouse gas removals (GGR) (Department for Energy Security and Net Zero 2026), along with its intention to align with the CRCF, offers one route for strengthening the integrity of biochar-based carbon storage. The Department for Environment,

Food and Rural Affairs (2026) (Defra) Sustainable Farming Incentive could provide a potential mechanism for integrating biochar into existing land-management payments (Cooke and Barling 2025; Dewally et al. 2025). This is one approach through which the diverse uses of biochar by farmers and other agricultural stakeholders—spanning soil health, biodiversity, farm business resilience, and carbon storage—could be incentivised. At present, biochar has received little serious consideration within Defra’s arrangements, which remain voluntary in their approach to realising environmental sustainability on farms. Ensuring that biochar governance reflects everyday agricultural realities, rather than being driven solely by carbon-market logics, will be important for legitimacy and engagement. These developments also highlight opportunities for further social science research to examine how emerging policy arrangements shape sociotechnical visions of biochar in UK agriculture.

Conclusion

This paper has critically examined the emerging socio-technical visions of biochar in UK agriculture, particularly in the context of greenhouse gas removal (GGR) and the wider net zero agenda. We have revealed the diverse ways in which biochar is being imagined, by whom and how, and what these visions indicate about the nature and degree of consensus and contestation surrounding biochar’s role in UK agriculture.

The analysis identifies two overarching sociotechnical visions. Firstly, a sociotechnical vision of biochar as a greenhouse gas removal approach produced at scale and applied to agricultural land, detailing both farmer alignment with and contestation of this approach. Secondly, a socio-technical vision of biochar for multiple on-farm benefits, including farm business benefits, enhanced agricultural production, and improved on-farm biodiversity. These findings demonstrate that biochar’s future in UK agriculture cannot be understood as a single trajectory aligned with net zero ambitions but instead reflects ongoing negotiation between competing sociotechnical visions of desirable futures.

More broadly, the paper contributes to the sociotechnical imaginaries and sociotechnical visions literature. It foregrounds the grassroots sociotechnical visions articulated by farmers and other agricultural stakeholders, alongside the more institutional sociotechnical visions and imaginaries typically emphasised in existing studies. In doing so, the paper demonstrates how attending to grassroots sociotechnical visions can surface forms of contestation and alternative future orientations that remain obscured when analysis focuses solely on elite or institutionally produced visions of sociotechnical futures. The paper shows how such

perspectives can enrich future analyses of sociotechnical futures.

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Declarations

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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