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Bridging Quantitative and Qualitative Science for BECCS in Abandoned Croplands

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Key Points:

- Mixed quantitative and qualitative methods are key to unravel the role of bioenergy and bioenergy with carbon capture and storage (BECCS) in climate change mitigation
- Ongoing recultivation of abandoned cropland for food production limits aboveground carbon accumulation from natural regrowth
- Policies to redirect recultivation toward BECCS are needed to maximize climate change mitigation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Bioenergy with carbon capture and storage (BECCS) plays a vital role in most climate change mitigation scenarios, where a solution for sustainable near-term bioenergy expansion is to grow energy crops such as perennial grasses on recently abandoned cropland. There is a need to combine model-based insights into theoretical potential and future biomass supply with more fine-grained sociotechnical analysis to move toward realistic policies and innovation strategies. We combine natural science insights anchored in quantitative bioenergy modeling with qualitative social science anchored in the multi-level perspective. Using these mixed methods enables a global-to-local-to-global level assessment of near-term bioenergy recultivation opportunities for abandoned cropland. Norway is the local case. There are three main findings. First, the ongoing recultivation trends for food/feed production risks making gains in aboveground carbon stocks from natural regrowth on the mapped abandoned cropland over a 30-year evaluation period almost negligible. Second, delaying a BECCS recultivation of abandoned cropland will make it impossible to reach high-end mitigation potentials, and an accelerated BECCS recultivation guided by a policy push is needed to ensure stronger mitigation. Third, we unravel several real-world challenges associated with bioenergy resource and supply modeling. Remote-sensing techniques alone cannot capture actual land availability for land-based climate change mitigation strategies. Local-level sociotechnical conditions are generally found insufficiently supportive to align with the rapid near-term bioenergy crop expansion found in 2°C scenarios from integrated assessment. The integration of mixed quantitative and qualitative methods is key to better understand the role of BECCS in climate change mitigation.

Plain Language Summary Bioenergy with carbon capture and storage (BECCS) is a key option for mitigating climate change. The idea is to capture the carbon emitted when biomass is converted into fuels or burned for energy production and store it underground. One proposed solution to ramp-up biomass supply involves growing energy crops, like perennial grasses, on recently abandoned farmland. To make realistic policies and strategies for the future, we need to connect the theoretical potential of BECCS with local context, considering social and technical factors. We combine two approaches: using numbers to model bioenergy and using social science to understand the human and political side. By using a mix of methods, we can assess the potential for a near-term recultivation of abandoned cropland for bioenergy and BECCS. There were three main findings. First, the combined use of both natural science and social science methods can help us better understand the role of BECCS in climate change mitigation. Second, re-using abandoned farmland for growing food or animal feed reduces the effectiveness of letting the land naturally recover for fighting climate change. Third a rapid BECCS recultivation of abandoned cropland increases achieved climate change mitigation relative to a delayed BECCS recultivation.

1. Introduction

Bioenergy with carbon capture and storage (BECCS) is important in most climate change mitigation scenarios (Rogelj et al., 2018), but we lack insights into the sociotechnical dynamics that can enable or disable its uptake. Integrated assessment models (IAMs) predict a large-scale expansion of dedicated non-food bioenergy crops to ramp-up biomass supply from the present-day 57 exajoule (EJ) year^{-1} to medians of 83–249 EJ year^{-1} by 2050 in 1.5°C scenarios (Rogelj et al., 2018) across the different Shared Socioeconomic Pathways (SSPs) where the temperature target could be met (all but SSP4) (Riahi et al., 2017). From this, medians of 36–197 EJ year^{-1} are predicted coupled to carbon capture and storage (CCS) across SSPs (Gidden et al., 2019; Rogelj et al., 2018). This corresponds to median land requirements of 210–670 million hectares (Mha) for dedicated second-generation

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non-food bioenergy crops (such as perennial grasses and short-rotation woody crops), equal to about 13%–42% of the current global cropland area extent (Shukla et al., 2019). These changes would entail broad shifts in agricultural practices and value chains, as well as sociocultural understandings of elements such as land and place.

The sustainability of dedicating large areas of land for bioenergy crop production has been contested for reasons concerning food security and biodiversity trade-offs (Anderson & Peters, 2016; Calvin et al., 2021; Vaughan & Gough, 2016). A promising strategy to limit such trade-offs is to grow perennial grasses on recently abandoned croplands (Baxter & Calvert, 2017; Campbell et al., 2008; Leirpoll et al., 2021; Næss et al., 2021). Abandoned cropland is attractive because it is typically located near existing infrastructure, and it has had limited time to restore ecosystem functionality and natural carbon stocks since the end of the farming activities (S. Li & Li, 2017). Cropland abandonment has historically emerged with societal changes such as urbanization, market changes, and agricultural intensification rather than when land has become uncultivatable (Dolton-Thornton, 2021; Lasanta et al., 2017; S. Li & Li, 2017). Recultivating abandoned cropland for bioenergy production can make a meaningful near-term contribution to increase global biomass supplies in line with climate change mitigation scenarios (Gvein et al., 2023; Leirpoll et al., 2021; Næss et al., 2021). For bioenergy recultivation to take place, there must be a demand for biomass driving land use change, a biophysical resource potential must exist, and local sociotechnical conditions must be sufficiently supportive.

Global-local frameworks are key for analyses of land use changes, associated sustainability implications, and the interlinkages between global drivers and local responses (Hertel et al., 2019). Important global drivers affecting land use change include population dynamics, consumption preferences, technological development, and climate change (Hong et al., 2021; Popp et al., 2017; Stehfest et al., 2019). The impact of global drivers at the local level depends on national and subnational contexts, such as natural resource availability, market integration, land use regulations, available technology and infrastructure, and socioeconomic conditions. Global drivers may induce either behavioral or production changes in local producers and consumers, which in turn will lead to land use change (Meyfroidt et al., 2013). National and subnational institutions may respond to global drivers by changing land use regulations and governance, which can give rise to associated feedback at both local and global levels (Meyfroidt et al., 2013). International bioenergy trade increases more rapidly in scenarios with stronger global policy-related efforts to mitigate climate change (Daioglou et al., 2020), which may incentivize near-term land use change in specific regions. At national and local levels, land use regulations may not only be designed to promote biomass production for land-based mitigation purposes, but also to limit potential sustainability trade-offs of large-scale bioenergy deployment and to prevent land use change in areas with primary natural vegetation or cropland conversion (Creutzig et al., 2015; Reid et al., 2020).

Integrated Assessment Modeling has provided gridded global projections of future land use changes (Chen et al., 2020a; Hurtt et al., 2020; van Vuuren et al., 2011) under diverse scenarios of socioeconomic development (the SSPs) (O'Neill et al., 2017) in combination with different Representative Concentration Pathways (van Vuuren et al., 2011), and shown widespread future deployment of dedicated bioenergy crops around the globe in stringent mitigation scenarios (Chen et al., 2020a). Although IAMs by combining information from multiple disciplines can provide insights useful for exploring the energy transition and global land use change, they have a limitation due to their aggregate orientation, and therefore there is a pressing need for complementary methods of analysis (Berndes & Cowie, 2021; Geels et al., 2016; Köberle et al., 2022). There is a need for better representation of real-world policies, aspects of innovation, and behavior change (Gambhir et al., 2019; Keppo et al., 2021). Especially, the underrepresentation of societal and governance aspects related to bioenergy and BECCS needs to be accounted for (Forster et al., 2020).

Studies that have assessed achievable bioenergy resource potentials of recultivation have primarily focused on biophysical potentials (Leirpoll et al., 2021; Næss et al., 2021, 2022), and they have typically relied on remote sensing and output from crop yield models. Previous efforts at assessing recultivation from the farmer's perspective have focused on opportunities for food production (Fayet et al., 2022; Prishchepov et al., 2021; Subedi et al., 2022), while the processes and practices that could enable local innovation for bioenergy recultivation have been underexplored. As bioenergy expansion is a major driver of land use changes in mitigation scenarios (Popp et al., 2017), there is a strong need to provide perspectives from the social sciences that would advance our knowledge of the role of such land in the current local social fabric. Applying the multi-level perspective (MLP) (Geels, 2002) gives us insights into how technical aspects interplay with social aspects, such as politics and different actors. The integration of insights from integrated assessments, bioenergy resource

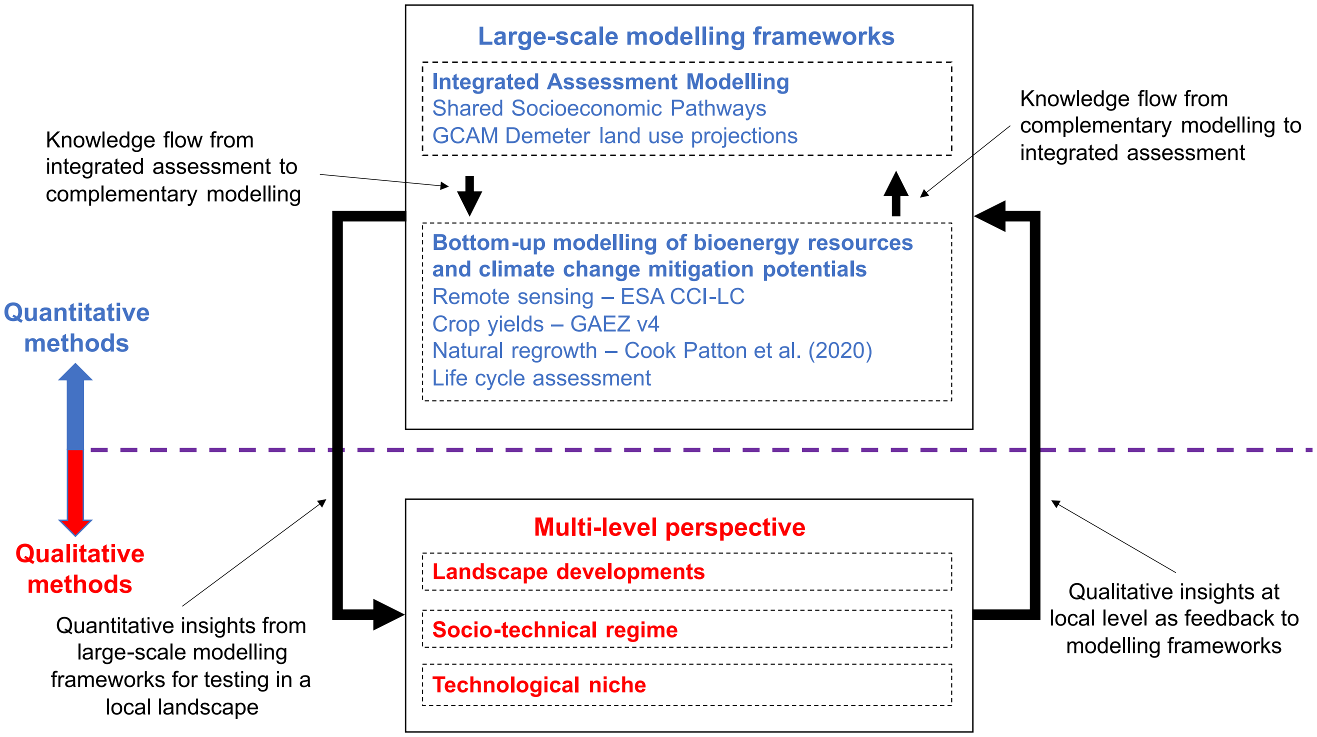

Figure 1. A schematic flow chart of the framework applied in this study to evaluate bioenergy with carbon capture and storage from abandoned cropland, including applied methods and data sets, contributions from quantitative and qualitative science, and knowledge exchanges between scientific disciplines.

modeling, and the MLP might allow us to propose more refined innovation and policymaking strategies, and to evaluate the feasibility of such strategies, as well as to provide insights that might improve the modeler's assumptions.

In our study we used mixed methods to provide a global-to-local-to-global level assessment of near-term bioenergy recultivation opportunities for abandoned cropland by bridging insights from quantitative and qualitative science (see Figure 1 for a schematic flow chart). We processed high-resolution global bioenergy land use projections from ambitious climate change mitigation scenarios (Chen et al., 2020a) to explore modeled effects of global drivers on future bioenergy crop deployment globally and in Norway. We quantified the bioenergy and climate change mitigation potentials of recently abandoned cropland as a near-term opportunity to deploy bioenergy crops sustainably. We used satellite observations to quantify cropland abandonment (Copernicus Climate Change Service, Climate Data Store, 2019; UCL-Geomatics, 2017, 2017) and used a crop yield model (Fischer et al., 2021) to assess the bioenergy productivity of three perennial grasses. We evaluated bioelectricity and Fischer-Tropsch (FT) diesel with CCS, and then quantified achievable climate change mitigation considering land use change emissions, CO_2 sequestered through CCS, and life-cycle emissions, and avoided emissions from energy substitution. Achieved BECCS mitigation was benchmarked against continued natural regrowth (Cook-Patton et al., 2020a), and this allowed us to identify the most promising Norwegian region for a bioenergy recultivation quantitatively. We focused on the local level to evaluate bioenergy crop deployment and abandoned cropland recultivation through a qualitative in-depth analysis.

In this paper, our aim is twofold. First, by building on a sociotechnical perspective anchored in the MLP (Geels, 2002), we contribute insights into the complexities involved in transition to widespread production of dedicated bioenergy crops for bioenergy, which require changes in agricultural regimes, practices, and crop value chains. Second, we investigate the gap between large-scale global modeling exercises, and local socioeconomic conditions, policies, and constraints. We bring much needed methods triangulation to bridge insights from the social sciences and natural sciences (see, e.g., Sovacool et al., 2018), to contribute insights that provide a more realistic image of the challenges and opportunities associated with a transition to large-scale energy transition, and the production of energy crops for bioenergy and BECCS. Based on mixed quantitative and qualitative insights, we designed six explorative scenarios to evaluate achieved climate change mitigation of different future abandoned cropland trajectories until 2050. We applied the explorative scenarios to the local, national, and global levels, thereby providing complementary insights that would be useful at multiple scales, including for local policymakers and stakeholders, bioenergy resource modeling, and land use modeling through integrated assessment.

2. Research Methods

2.1. Future Bioenergy Land Use

We obtained global gridded land use projections toward 2100 at 0.05° resolution (about 6 km) from Chen et al. (2020a) and Vernon et al. (2018). The projections were produced by both the Global Change Assessment Model (GCAM) v5.1 (Calvin et al., 2019) and the downscaling model DEMETER (Chen et al., 2019; Vernon et al., 2018). All SSPs in combination with RCP2.6 where the mitigation target could be met were considered (i.e., consistent with 2°C of global warming in 2100 relative to pre-industrial levels). This included SSP1 (Sustainability) (van Vuuren et al., 2017), SSP2 (Middle of the road) (Fricko et al., 2017), SSP4 (Inequality) (Calvin et al., 2017), and SSP5 (Fossil-fueled development) (Kriegler et al., 2017). We considered GCAM final land use types 29 and 30 (rain-fed and irrigated bioenergy crops) and quantified bioenergy land use over time. These projections were designed to provide a comprehensive future land use product for earth system modeling, but they have also been advocated as a data set suitable for assessing how human activities affect “the whole Earth” system through agricultural activities and energy production, and for socioeconomic analysis (Chen et al., 2020a).

In GCAM, economic and energy systems are represented as 32 geopolitical regions, providing insights into international socioeconomic and energy dynamics (Calvin et al., 2019). Land and water systems are further subdivided into 384 land-water regions based on major water basins (Calvin et al., 2019), which allows for the representation of interactions between agriculture and land and water resources. Bioenergy competes for land based on profitability, and there is a market for bioenergy trade. In our study, we specifically quantified future bioenergy land use in Norway by using gridded country masks obtained from CIESIN (Center for International Earth Science Information Network, 2023) to filter GCAM data. In GCAM, Norway is part of the European Free Trade Association geopolitical region comprising Norway, Switzerland, and Iceland, and there is an independent Norwegian land-water region (Calvin et al., 2019).

2.2. Abandoned Cropland

We derived satellite-based estimates of cropland abandoned between 1992 and 2020 by combining two consistent data sets from: (a) European Space Agency's Climate Change Initiative Land Cover (ESA CCI-LC) product (UCL-Geomatics, 2017, 2017) and (b) the Copernicus Climate Change Service climate data store (Copernicus Climate Change Service, Climate Data Store, 2019). These annual data sets have a spatial resolution of 10 arcseconds (about 300 m at the equator), and they each contain 37 different land cover classes, of which four represent complete cropland classes and two represent mosaics of cropland and natural vegetation. The data sets achieve an overall global accuracy of 71% (UCL-Geomatics, 2017). When used for abandoned cropland mapping, the data sets achieve an overall accuracy of 83% globally and 79% in Europe (Zheng et al., 2023). The data sets have not been specifically validated for Norway, but a previous study showed respective user and producer accuracies of 63% and 65% for cropland classes in the neighboring country of Finland, which has similar climatic conditions (Karvonen et al., 2018).

Abandoned cropland was mapped as any individual pixels transitioning from one of the six cropland classes in 1992 to any of the classes representing natural vegetation in 2020, following the corresponding IPCC land categorization of ESA CCI-LC (UCL-Geomatics, 2017, 2017). We excluded pixels transitioning to urban areas, but we included transitions from complete cropland to cropland mosaics. For every pixel with identified abandonment, we identified the most recent year before cropland contraction. Our approach was consistent with approaches used in previous studies that mapped cropland abandonment using the same data set (Leirpoll et al., 2021; Næss et al., 2021). The abandoned cropland map was upscaled 30 arcseconds to match the natural regrowth data set, and to 5 arcminutes to match the resolution of the crop yield model.

Recultivation of abandoned cropland over time can be modeled based on abandonment half-life (i.e., time required for half of the abandoned cropland to be recultivated) using a decay function (Crawford et al., 2022). In our study, we parameterized an exponential decay function to predict how long abandoned cropland pixels would remain abandoned in the future (Equation 1):

$$A(t) = A_0\, 2^{-t/t_{1/2}} \tag{1}$$

where A is area remaining abandoned over time t, A_0 is initial abandoned land extent, and $\boldsymbol{t}_{1/2}$ is abandonment half-life. Equation 1 was applied to every grid box with identified abandoned cropland using scenario-specific abandonment half-life parameterization and scenario-specific diversion of recultivated land to food/feed or bioenergy production (see Section 2.7). For future land use changes, we dynamically treated each pixel as a mosaic with fractions of sub-classes (non-abandoned cropland, and abandoned cropland that (a) remains abandoned, (b) has been recultivated for food/feed production, (c) has been recultivated for bioenergy crop production for bioelectricity, and (d) has been recultivated for bioenergy crop production for biofuels).

2.3. Bioenergy Crop Productivity

We considered three perennial grasses—reed canary grass (*Phalaris arundinacea*), switchgrass (*panicum virgatum*), and miscanthus (*Miscanthus × giganteus*)—for bioenergy deployment on abandoned cropland. Gridded bioenergy dry mass yields of perennial crops were obtained from the parameterized bioenergy crop yield model Global Agro-Ecological Zones (GAEZ) v4 (Fischer et al., 2021) driven by climatic conditions for a 30-year period centered on the 2020s from the Norwegian Earth System Model (Seland et al., 2020) (Figures S1a–S1c in Supporting Information S1). GAEZ has been extensively used to model bioenergy crops (Næss et al., 2021; Staples et al., 2017, 2018) and has been validated against observational data (S. Li & Li, 2017) for perennial grasses (Gvein et al., 2023; Næss et al., 2022). We considered a modern agricultural system with closing rain-fed yield gaps reliant on high levels of mechanization and optimal pesticides and fertilizer use. GAEZ dry mass yields were converted to bioenergy and carbon yields. Lower heating values of 18.06, 17.82, and 18.55 gigajoules (GJ) per ton dry mass and carbon contents of 0.46, 0.46, and 0.48 were considered for reed canary grass, switchgrass, and miscanthus, respectively (ECN.TNO, 2019). The bioenergy crop distribution was spatially optimized to maximize energy production (Figure S1d in Supporting Information S1). Bioenergy potentials of abandoned cropland were calculated as the product between abandoned cropland availability and bioenergy yields for each grid cell at 5 arcminutes resolution. We identified the regions and municipalities with the highest bioenergy potentials locally in Norway.

2.4. Final Energy, Natural Regrowth, and Climate Change Mitigation

We considered biomass conversion pathways to bioelectricity and FT diesel coupled to CCS. These two pathways were parameterized using multi-study mean life-cycle emission and conversion efficiencies based on a previous work (Hanssen et al., 2020) that reviewed available literature (see Table S1 in Supporting Information S1, for parameterization details). Following Hanssen et al. (2020), we spatially quantified life cycle emissions of bioenergy production at 5 arcminutes resolution for a 30-year period, considering the individual emission modeling elements of on-farm activities, supply chains, energy conversion, and land use change (i.e., the difference between aboveground carbon stocks with bioenergy recultivation against a natural regrowth benchmark at the end of the evaluation period). Biomass stocks that had accumulated since abandonment were assumed combusted at site with an associated instant emission pulse.

We used a data set of aboveground carbon accumulation from natural regrowth (30 arcseconds resolution) to quantify historically accumulated carbon on abandoned cropland and to benchmark future natural regrowth (Cook-Patton et al., 2020a). The data set was produced using machine-learning based on information from 13,112 individual georeferenced measurements of natural regrowth (Cook-Patton et al., 2020a). Thereafter, we integrated the data set into our cropland abandonment map. We calculated future carbon accumulation of continued natural regrowth as an alternative abandonment trajectory (Figure S2 in Supporting Information S1) and historical carbon accumulation on abandoned cropland based on the period since abandonment (Figure S3 in Supporting Information S1).

The BECCS process is attractive in climate change mitigation because it offers the opportunity to supply renewable energy and simultaneously remove atmospheric carbon dioxide through CCS and long-term carbon storage in geological reservoirs (see also Text S1 in Supporting Information S1). Climate change mitigation is defined as the net effects of carbon sequestration or emissions (e.g., carbon pulses from land clearing, on-farm activities, supply chains, ongoing natural regrowth, and CCS), and avoided emissions from fossil fuel substitution over a given period. This definition is consistent with the definition used by Gvein et al. (2023). We considered avoided emissions from 1:1 energy substitution based on technology-specific life-cycle emission factors (Hanssen et al., 2020; Hertwich et al., 2015; Scarlat et al., 2022) (see Table S2 in Supporting Information S1, for parameterization details). For the dynamic analyses, we calculated final energy produced based on predicted bioenergy recultivation over time. Similarly, carbon emissions or sequestration, and avoided emissions were allocated after timing of occurrence. For simplicity, we assumed that predicted recultivation would be evenly distributed landscape-wide across abandoned cropland that showed bioenergy productivity.

2.5. In-Depth Interviews and Document Analysis

We conducted qualitative studies to identify local constraints to and enablers for the establishment of an energy crop niche in one of the municipalities (Malvik) quantitatively identified as having amongst the highest bioenergy resource potential from abandoned cropland locally in Norway. As we had adopted a sociotechnical perspective, we were interested in the broad set of activities of different actors that would need to materialize for a new value chain to emerge. The municipality was selected as an instrumental case study (Stake, 2000), meaning that we use the case mainly to gain insights into the issue of energy crop recultivation in the county of Trøndelag and Norway.

We conducted 10 in-depth interviews to solicit views on the local possibilities and challenges. We interviewed administrative staff in the municipality and the Trøndelag county, local farmers, and local researchers with knowledge of local land use and bioenergy innovation. All interviews were audio-recorded and transcribed (see Table S3 in Supporting Information S1). Most of the interviews were done online due to corona restrictions. Before the interviews the informants received a preliminary research note informing them about Norwegian cropland abandonment hotspots and recultivation potentials for bioenergy. This served as a common starting point. We then used in-depth interviews where we asked about “is there a market for energy crops in Norway?” and “what are the advantages of reed canary grass as an energy crop?.” To the grain- farmers we used a shorter and more direct type of interviews (i.e., focus interviews), suitable for more specialized topics (Tjora, 2018). We asked questions as “what would it take for you to start producing energy crops?” and “what are the obstacles to this on the abandoned field of today?.” The interviews achieved a saturation level after these 10 interviews because of the specific topic regarding possibilities and barriers for grooving energy crops on abandoned land (Ryen, 2002). To supplement the interviews, we performed a document analysis. We reviewed relevant policy documents and strategies at municipal, regional, and national level.

2.6. The Multi-Level Perspective

We used the MLP as a guide to explore relevant existing regimes and existing transition strategies, as well as potential links between them and a hypothetical energy crop niche in the central region of Norway (Geels, 2002; Rip & Kemp, 1998). The MLP allows for a three-level conceptual distinction between niches, regimes, and landscapes. Our key analytical focus is on the relationship between an existing agricultural regime, the way this regime relates to abandoned land, and a potential niche recultivation of such land with a new energy crop. Regimes constitute quite stable meso-level structures containing the dominant “products and technologies, stocks of knowledge, user practices, expectations, norms, regulations etc.” (Markard & Truffer, 2008, p. 603). Geels (2004, 2004, 2011) posits that sociotechnical regimes are deep structures, a metaphorical form of grammar, or sites that strongly structure local practices. Here, the regime we examine consists of, existing farming practices and value chains, national and local policies that uphold those practices, and markets for existing crops. Elements that are understood as configuring current crop production in an identified region.

Within the MLP, niches are typically where innovations are identified (Raven et al., 2016). Many MLP studies have analyzed the dynamics that enable niche technologies or practices to destabilize or change existing regimes, such as when a system of electromobility replaces a system of combustion engines (Bjerkan & Seter, 2021; Skjølsvold & Ryghaug, 2020). However, the development of niches is a form of work that requires social processes beyond the development and implementation of technology. Typically, it entails shaping shared visions and expectations, building strong networks, and instigating processes that enable new forms of learning as a way of supporting niches (Fjellså et al., 2021; Sovacool et al., 2020; van der Laak et al., 2007), but often also policies that seek to weaken existing regimes (Kivimaa & Kern, 2016). Researchers have noted the centrality of various

Table 1
Explorative Scenarios Describing Future Pathways That Abandoned Cropland Might Follow Toward 2050

Scenario	Abandonment half-life $t_{1/2}$ (years)	Share of recultivation to food/ feed production	Share of recultivation to BECCS bioelectricity	Share of recultivation to BECCS Fischer-Tropsch diesel
Continued natural regrowth	∞	N/A	N/A	N/A
Recultivation, food/feed production	23	100%	0%	0%
Recultivation, BECCS bioelectricity	23	0%	100%	0%
Recultivation, BECCS FT diesel	23	0%	0%	100%
Accelerated recultivation, BECCS bioelectricity	11	0%	100%	0%
Accelerated recultivation, BECCS FT diesel	11	0%	0%	100%

Note. Abandonment half-life refers to the time taken for half of the abandoned cropland at an aggregate level to be recultivated.

types of technological, institutional, or place-bound experiments championed by different types of actors in enabling such changes (Sengers et al., 2019). The landscape refers to large and often exogenous macro developments, which can also have important bearings on innovation activities.

The MLP helps us grapple with the relationship between both quantitative predictions and what looks feasible on the ground. As Pandey et al. (2021) note, quantitative estimates can come with large uncertainty. Conversion from bioenergy resource potentials to realized value is challenging, because novel bioenergy feedstocks are not an "off-the-shelf commodity" (Pandey et al., 2021), and that realizing any potential will require careful negating of social and technical elements. Sherrington et al. (2008) similarly argue that the techno-economic potential for growing energy crops needs to be mediated through an understanding of other aspects, such as farm-level constraints. In Text S2 in Supporting Information S1, we present a review of past research focusing on sociotechnical aspects of enabling energy crop-based industries. While none of these studies focused on the recultivation of abandoned cropland, the dynamics illustrated are relevant to our own inquiries because show the complexities of changing agricultural regimes.

2.7. Explorative Scenarios Designed Through Mixed Methods

We designed a set of explorative scenarios to unravel the climate change mitigation potentials of future abandoned cropland trajectories toward 2050 (Table 1). The scenarios rely on combined insights from quantitative bioenergy modeling and qualitative in-depth analysis. For a business-as-usual scenario, we considered a recultivation for food and feed production scenario where the historical pace of global recultivation (mean abandonment half-life of 23 years) continues also in the future (Crawford et al., 2022). Continued natural regrowth was used as an additional benchmark, assuming strict land management policies to prevent recultivation. Four scenarios with gradual BECCS deployment on abandoned cropland were considered, representing implementation of policies to promote bioenergy recultivation. We explored the effect of different bioenergy recultivation rates (following historical trends for either food/feed recultivation or an accelerated recultivation) and two different conversion pathways (FT diesel and bioelectricity). In addition to the local and national level, we also made a local-to-global application for the explorative scenarios, as the parameterization was based on a study that evaluated recultivation rates for 11 different locations around the globe (Crawford et al., 2022).

3. Results and Discussion

As global drivers are essential to understand local-level land use change, we departed from the future gridded projections of global bioenergy land use by Chen et al. (2020a). We also built on the global-level insights of Gvein et al. (2023) regarding near-term opportunities to utilize abandoned cropland for climate change mitigation and provided updated estimates of resource potentials.

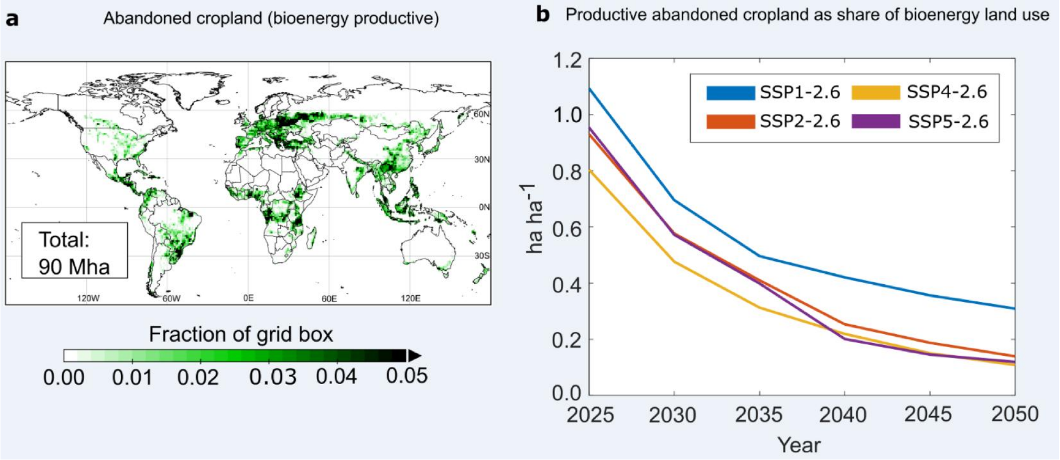

Figure 2. Potential contribution of abandoned cropland to ramp-up near-term bioenergy supply in line with SSPx-RCP2.6 scenarios. (a) Abandoned cropland that show bioenergy productivity (predicted bioenergy yields above zero) given as fraction of grid box. (b) Bioenergy productive abandoned cropland extent (with predicted bioenergy yields above zero) as share of future bioenergy crop land use in Global Change Assessment Model Demeter SSPx-RCP2.6 scenarios.

3.1. Global Opportunities to Ramp-Up Bioenergy Supply With Abandoned Cropland

We found 106 Mha of abandoned cropland between 1992 and 2020, out of which 90 million hectares (Mha) of abandoned cropland showed bioenergy crop productivity (predicted bioenergy yields above zero) (Figure 2a). Bioenergy-productive abandoned cropland equaled 48%–70% of projected global bioenergy crop land use in 2030 in GCAM SSPx-RCP2.6 scenarios (Figure 2b). If instantly recultivated for BECCS and evaluated over a 30-year period, abandoned cropland has the potential to provide annual average mitigation equivalent to 2%–9% of current annual global anthropogenic CO_2 emissions (Friedlingstein et al., 2022), depending on energy conversion pathways and achieved substitution of fossil fuels (Figures S4 and S5 in Supporting Information S1). This highlights the near-term opportunities associated with utilizing abandoned cropland for BECCS. An in-depth analysis of future projected global bioenergy expansion and mitigation opportunities from abandoned cropland is provided in Text S3 in Supporting Information S1.

The above-mentioned global estimates are discussed in detail in Section 3.8, where they serve as a benchmark for evaluating the effect of recultivation rates on mitigation potentials. They also serve as a key motivation for deep local-level analysis, providing vital context as we examine the Norwegian case in depth by applying the MLP theory, thereby providing a basis for investigating the real-life local feasibility of modeled land use projections, actual utilization of modeled bioenergy resource potentials, potential deployment barriers, and how local and national institutions may facilitate or prevent bioenergy crop (re)cultivation through policy instruments.

3.2. Projected Bioenergy Land Use and Potential Near-Term Contribution of Abandoned Cropland in Norway

The global gridded land use projections predicted that bioenergy crop land use in Norway will rapidly increase to 966–1,054 kilo hectares (kha) by 2030 in GCAM SSPx-2.6 scenarios (Figure 3a), comparable to the current Norwegian agricultural land use extent (FAO, 2023). By 2050, bioenergy land use expands further to either 3.0–7.9 Mha or several times the current agricultural land use extent. For comparisons, the current area extent of productive Norwegian forests (a proxy for managed forestry) is about 7.0 Mha (Statistics Norway, 2023). Such extreme land use changes would turn Norway into a major bioenergy actor. In GCAM, bioenergy competes for land based on profitability (Iyer et al., 2022), and a key insight from GCAM is therefore that global drivers and climate action may lead Norway to develop its bioenergy sector. The projected scale indicates a major expansion into areas with natural vegetation or forests that are currently managed. This is likely to cause controversy, given the strong interests that favor nature conservation in Norway (Sovacool et al., 2022). Managed forests are not used for bioenergy in GCAM, and the predicted bioenergy land use refers to lignocellulosic bioenergy crops such as perennial grasses and short-rotation woody crops (Daioglou et al., 2020). As Norway currently lacks bioenergy

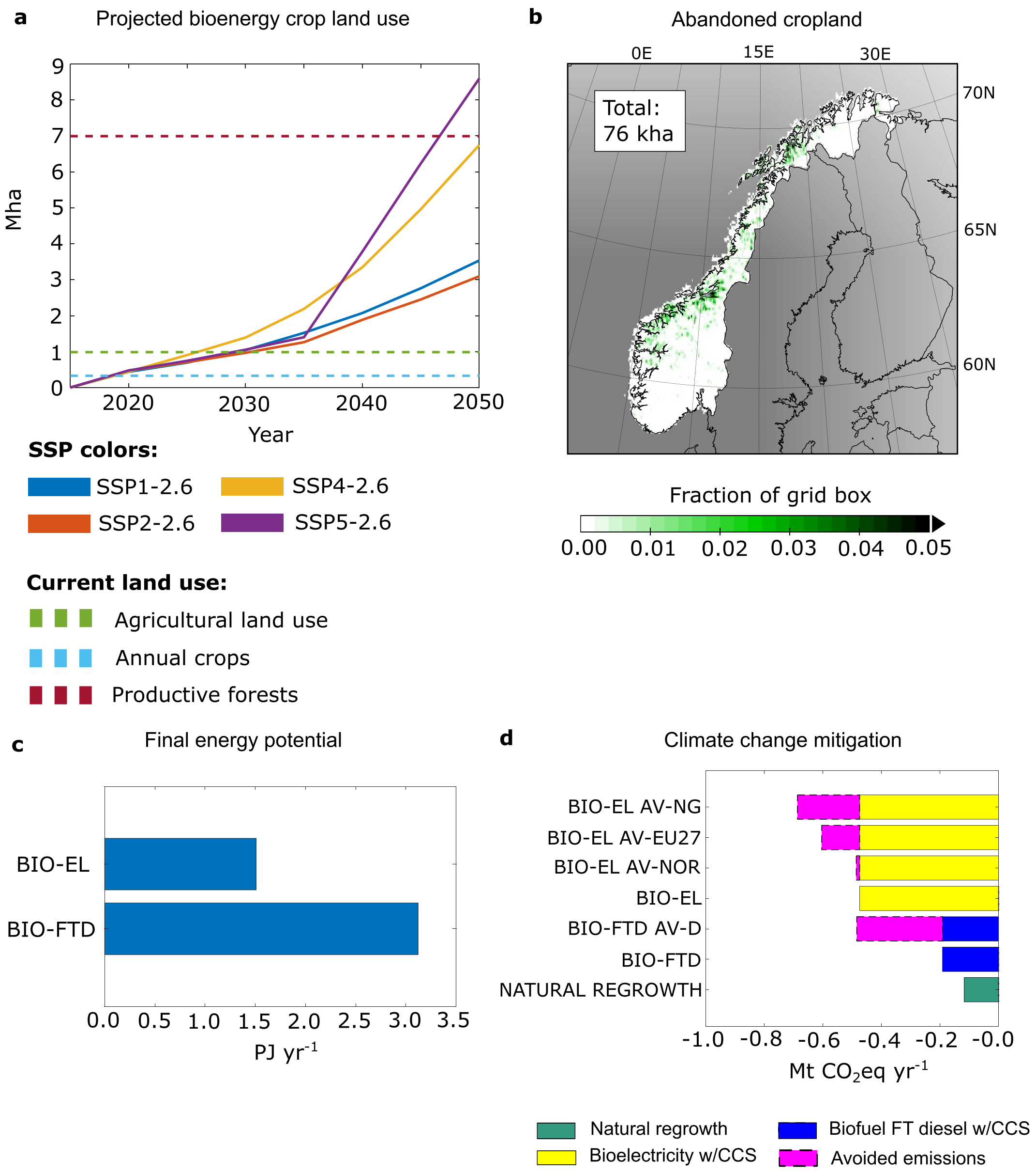

Figure 3. Norwegian bioenergy land use in future projections, abandoned cropland, final energy potentials, and climate change mitigation potentials. (a) Projected Norwegian bioenergy land use in Global Change Assessment Model SSPx-RCP2.6 scenarios. (b) Abandoned cropland as a fraction of grid box at 5 arcmin resolution. (c) Final energy potentials considering bioelectricity coupled to carbon capture and storage (CCS) (BIO-EL) and Fischer-Tropsch biodiesel coupled to CCS (BIO-FTD). (d) Potential contribution of abandoned cropland to climate change mitigation if recultivated for bioenergy with carbon capture and storage and under continued natural regrowth over a 30-year evaluation period. Current land use in (a) represent the area extent in 2020 as reported for agricultural land use and annual crops by FAO (2023) and productive forests by Statistics Norway (2023). Avoided emissions from energy substitution in (d) are avoided emissions from fossil fuels (e.g., diesel [AV-D]) and from other electricity generation methods (e.g., natural gas [AV-NG], EU27 grid-mix [AV-EU27], and Norwegian grid-mix [AV-NOR]).

crop production at scale, a first step to ramp-up supply involves finding near-term sustainable options for land use change and identifying the policy instruments that might help establishing the first bioenergy crop niche.

We found 76 kha of abandoned cropland in Norway based on satellite observations that could be targeted for near-term bioenergy expansion (Figure 3b). While this is a low absolute area extent in the global context, Norway shows an abandonment intensity close to the global country-level mean (Figure S6 in Supporting Information S1), thus indicating average near-term recultivation opportunities (e.g., relative to the national size of the country's agricultural sector).

About 75% of Norwegian abandoned cropland shows bioenergy crop productivity (57 kha). All areas are allocated to reed canary grass, and final energy potentials are 1.5 and 3.2 PJ year^{-1} for BECCS electricity and FT diesel, respectively (Figure 3c). Without fossil fuel substitution, BECCS can achieve mitigation of 0.2–0.5 MtCO$_2$eq year^{-1}, 0.1–0.4 MtCO$_2$eq year^{-1} higher than the natural regrowth benchmark (0.1 MtCO$_2$eq year^{-}) (Figure 3d). Considering avoided emissions from energy substitution, achieved mitigation can increase to 0.5–0.7 MtCO$_2$eq year^{-1}. For bioelectricity, avoided emissions from substituting Norwegian grid electricity is nearly negligible (1% change), and substitution of European grid electricity or natural gas as a marginal energy generation method is necessary to increase climate benefits—27% and 45% change, respectively. Compared with current annual emissions to air from road transportation in Norway (8.7 MtCO$_2$eq year^{-1}) (Statistisk sentralbyrå, 2022), achievable mitigation from continued natural regrowth and BECCS is 1% and 2%–8%, respectively.

3.3. Local Bioenergy Resources From Abandoned Cropland

In Norway, cropland abandonment is most intense in the central parts (28%) and northern (42%) parts of the country (Figure 4a). The regions with the most abandoned cropland are Trøndelag (21 kha), Troms og Finnmark (18 kha), Nordland (13 kha), Møre og Romsdal (11 kha), and Vestland (7 kha). Cropland abandonment is unequally distributed across municipalities (Figure 4b). About 60% of the abandoned cropland is found in the top 10% of municipalities experiencing the strongest abandonment. Trøndelag has the most abandoned cropland, mainly distributed along Trondheim Fjord (Figure 4c). Our estimates are generally consistent with previous assessments (See Table S4 in Supporting Information S1), including a non-remotely sensed estimate that found 18 kha of potentially abandoned land in Trøndelag based on farmer's applications for production subsidies (Mathiesen, 2019). For comparison, projected bioenergy crop land use across SSPx-RCP-2.6 scenarios in Trøndelag is 50–89 kha in 2030 (Figure S7 in Supporting Information S1), and the extent of abandoned cropland equals 24%–42% of it. Targeting these areas could contribute toward meeting near-term bioenergy land use projections, but further deployment would likely involve land grabs from ongoing food production, managed forestry, or areas with primary vegetation.

Regional bioenergy potentials (Figure 4d) are heavily affected by predicted bioenergy yields. Troms og Finnmark shows relatively high abandonment, but the bioenergy potential is low (0.49 PJ year^{-1}) because mean bioenergy yields are poor (26.8 GJ ha^{-1} year^{-1}). Trøndelag (3.1 PJ year^{-1}), Møre og Romsdal (1.1 PJ year^{-1}), and Vestland (1.0 PJ year^{-1}) show the highest regional bioenergy potentials. Bioenergy yields are consistently higher than the national average (>95 GJ ha^{-1} year^{-1}) in these regions (147, 107, and 145 GJ ha^{-1} year^{-1}, respectively). A cluster of 10 neighboring municipalities (Steinkjer, Inderøy, Verdal, Levanger, Stjørdal, Malvik, Trondheim, Selbu, Melhus, and Orkland) located along the southeastern side of the Trondheim Fjord achieved a combined potential of 1.9 PJ year^{-1} (Figure 4e) and a mean bioenergy yield of 173 GJ ha^{-1} year^{-1}. Based on biophysical modeling, we identified Trøndelag as a key candidate region in Norway for early bioenergy deployment on abandoned cropland (Figure 4f).

3.4. Local Sociotechnical Conditions Affecting the Feasibility of an Energy Crop Niche

Based on our quantitative findings, we conducted qualitative studies in the Trøndelag region of Norway. We focused on Malvik Municipality to understand the opportunities and challenges for establishing an energy crop niche in the region. The work was informed by interviews held with regional stakeholders, and by regional policy and strategy documents. Malvik serves as an *instrumental case* study (Stake, 2000). There are good reasons to believe neighboring municipalities would have yielded similar results. They are all farming municipalities affected by national legislation, specifically the 1995 Land Act (Landbruks- og matdepartmenetet, 1995), the socio-economic status of the population are the same, and they are all located close to the regional city, Trondheim (Statistisk sentralbyrå, 2023a, 2023b, 2023c). Due to the municipalities' proximity to Trondheim, there is also pressure on their agricultural land, where urban property development is increasing (Vinge & Sørensen, 2020).

At the beginning of 2016, Malvik had just over 13,700 inhabitants, as well as a strong agricultural identity and history (Malvik Bondelag, 2016). Around 8.8% of the municipality is cropland, and 1.1% of the population works

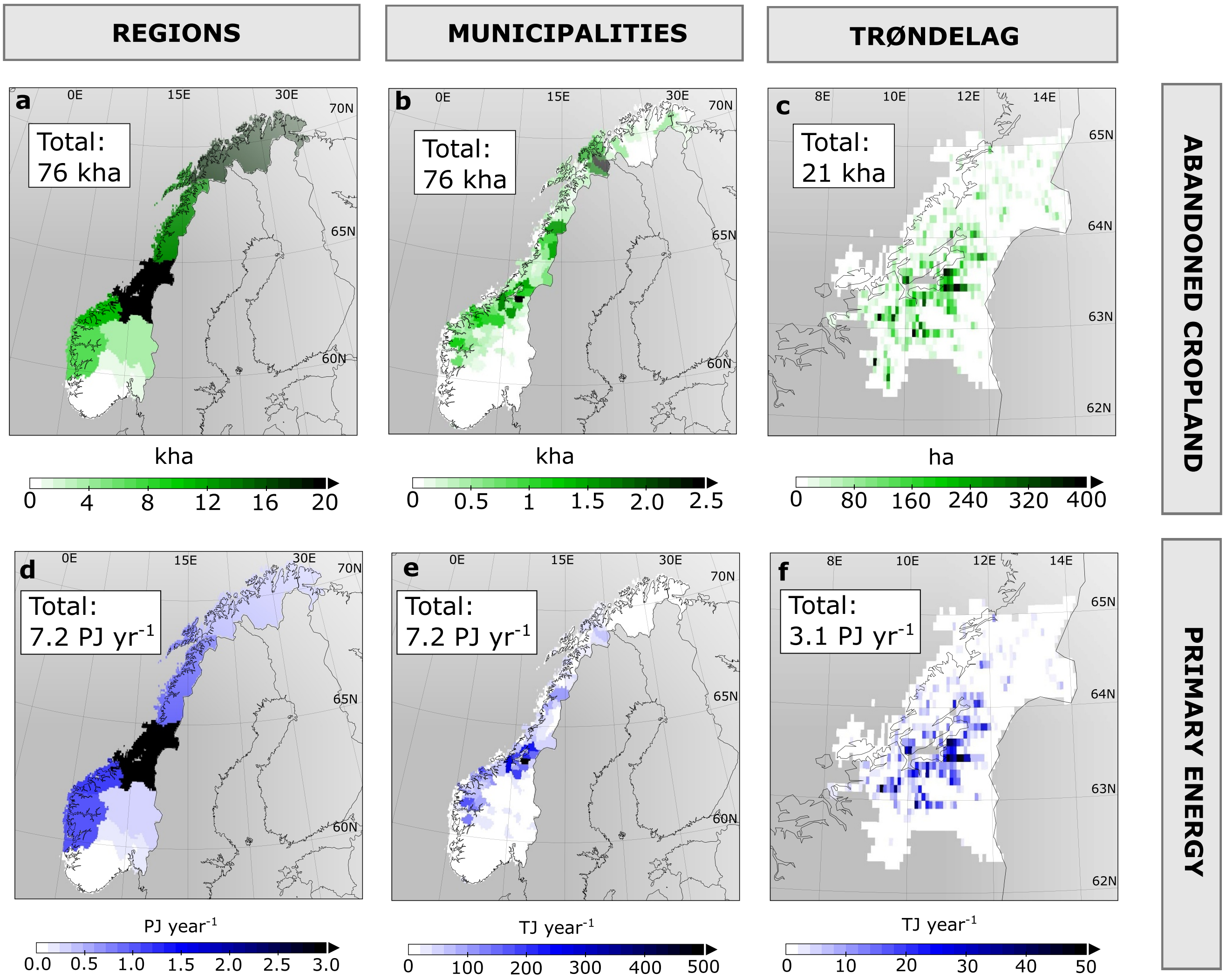

Figure 4. Bioenergy potentials of abandoned cropland in Norway. Abandoned cropland (kha) is shown per region (a), municipality (b), and Trøndelag region (c). Bioenergy potential (PJ year^{-1}) is shown per region (d), per municipality (e), and Trøndelag region (f).

in the agricultural sector (Malvik Bondelag, 2016). The population has grown steadily in recent years, in contrast to many other Norwegian agricultural municipalities. The growth can be attributed to Malvik's proximity to Trondheim, Norway's third largest city, where many Malvik dwellers commute daily for work (Statistisk sentralbyrå, 2023a). Figure S8 in Supporting Information S1 illustrates where arable land is found in the municipality, as well as the distribution of grain cultivation and grass-feed cultivation in the municipality (NIBIO, 2023).

3.5. Municipal, Regional, and National Policies and Strategies

The Malvik municipal land use strategy for 2020–2023 states that land for food crop production should be maintained (Malvik kommune, 2020). Financial incentives are available for farmers seeking to expand and diversify food crop production (Malvik kommune, 2020). The agricultural regime prioritizes measure to deter the abandonment of land.

Regional policies affect future opportunities for enabling a new energy crop niche. Trøndelag's action plan for climate transitions (Trøndelag fylkeskommune, 2020) has strong ambitions for energy transitions, focusing on renewable energy production, energy efficient buildings, and sustainable transport. Official descriptions of regional bioenergy activities highlight that forestry is currently the key outlet. When highlighting future avenues of innovation, these descriptions focus on biogas production, though noting that this does not tend to be financially viable for farmers today (Trøndelag fylkeskommune, 2020). Trøndelag also has a regional commercial

Table 2
Relevant Agricultural and Climate Policy Goals at Municipal, Regional, and National Levels

Level	Relevant agricultural policy goals and strategies	Relevant energy and climate policy goals and strategies
Municipal	Expand and diversify food production, avoid the abandonment of land	Increase renewable energy production and energy efficiency; biogas seen as a future option
Regional	Expand food production, increase value creation, climate adaptation, increased local energy production	Increase renewable energy production, energy efficiency, transport decarbonization, stimulate bioeconomy value creation; biogas from animal waste seen as a promising option for agricultural innovation
National	Preserve cultivated land, advance agriculture for carbon capture, electrification of farm machinery, use waste products in biogas production, increase local energy production	Advance local heating based on bioenergy, advance biogas, advance biochar for carbon uptake

program to support agricultural innovation. Key goals include increasing food and crop production and avoiding land abandonment, but also increasing value creation, advancing climate adaptation, and increasing energy production (Trøndelag fylkeskommune, 2018).

There is a strong energy transition ambitions in the Trøndelag region, but little focus on bioenergy; those that do so, focus on forestry bioenergy. Importantly, regional policy documents also point out the centrality of national policies and strategies, such as the national agricultural climate plan (Meld. St. 13, 2020–2021) and the national Land Act (Landbruks- og matdepartmenetet, 1995) for the opportunities they provide for local farmers to act and either shift or expand their focus.

The national agricultural climate plan is ambitious regarding reducing emissions and increasing innovation and value creation in the Norwegian agricultural sector (Innovasjon Norge, 2023). Farmers are envisioned to play a crucial role in producing bioenergy over the coming years, primarily through using waste products from farms in biogas production. The national Land Act (Landbruks- og matdepartmenetet, 1995) was a central document in our research. It requires that all owners of fully cultivated land and infield pastures have a duty to maintain those lands and pastures. Landowners are obligated to take care of the land not only for themselves but also for future generations. When landowners cannot or do not want to continue cultivating the land, they must ensure that others cultivate it for them, typically through a rental agreement with other farmers. This practice has increased since the mid-1990s due to the decreasing monetary compensation to small farms (Forbord et al., 2014).

Agriculture and bioenergy also play a role in national climate policies. The government's climate plan for 2021–2030 notes that the agricultural sector should both decrease greenhouse gas emissions and increase the uptake of carbon. Through the agency Innovation Norway, the national authorities have a program dedicated to advancing agriculturally oriented bioenergy (Innovasjon Norge, 2023). The program has a strong emphasis on advancing farm-level local heating based on biomass, biogas production, electricity production from biogas, and deploying biochar for carbon sequestration. Relevant agricultural and climate policy goals at municipal, regional, and national level are summarized in Table 2.

The above discussions paint a picture of an agricultural regime, which across governance levels is strongly geared toward avoiding cropland abandonment, with incentives intended to improve agricultural productivity and diversify food production. There is a strong policy pressure across the three levels for farmers to engage in sustainability transitions-oriented activities—policies that arguably stimulate a diversity of niches in which local farmers can engage. The cultivation of dedicated energy crops has not been articulated as an opportunity, interest, or either a strategic goal or policy across any of the above-mentioned governance levels. This points toward opportunities for experimenting with policies, but if an energy crop niche is to emerge, it first needs to be articulated as an opportunity, coupled with the development of policy strategies and instruments that would strategically make it relevant for communities across different governance levels.

3.6. Policy, Practice, and Markets

While the discussion in the preceding section points toward a strong policy pressure for preserving cultivated soil for food crops, our satellite data suggest that there does exist abandoned cropland in Malvik Municipality, as well as in the wider Trøndelag region. This is corroborated by data from the Norwegian Institute of Bioeconomy Research. Previously cultivated land in Malvik that in 2018–2020 was listed as potentially not cultivated, based

Figure 5. Abandoned cropland (shaded orange) identified in Malvik Municipality, 2018–2020. Based on data from https://kilden.nibio.no/ (accessed 5 May 2022).

on non-remotely sensed data (mainly historical agricultural production subsidy applications) (Mathiesen et al., 2019) is indicated in Figure 5.

Some elements of Figure 5 are important. First, the plots of land are few and scattered throughout the municipality. Our interviewee with expertise in bioenergy and energy crops noted that the situation was not ideal: “If there is a small plot of land here and a small plot there then it will be irrational and expensive to operate those areas” (Interviewee 4). Scale and volume represents challenges for actors seeking to establish an energy crop niche. National and sector-wide policy experimentation may be just as important as local work to stimulate land recultivation with energy crops.

Second, there is strong pressure from the municipal and regional authorities to try to bring many of these plots back into cultivation. The 1995 Land Act requires that previously cultivated land should be rented out (Landbruks- og matdepartmenetet, 1995), which suggests that many such plots may be temporarily out of operation, for example, due to the death of a farmer, a farmer moving away or for other reasons having stopped cultivation and not yet found a substitution. Our interviewees agreed with the goals of these policies, highlighting that abandoned cropland should be remobilized as grazing fields or for grain cultivation. One of our interviewees argued “If land is not used, we need to get the animals back out again, and we need to use that land for other crops than energy crops” (Interviewee 7). The interviewees' views were legitimated by reference to the fact that only 3% of Norway is arable (Landbruks- og matdepartementet, 2021), and that as much land as possible should be mobilized for food production.

The above discussion on policy strengthens previous assertions by scholars that Norwegian farming is highly structured by existing policies and that farmers often lack the agency to make changes (Ravenscroft, 1999).

Third, our interviews and communication with the municipal administrative staff and with farmers suggests that much of what is listed as abandoned farmland might be due to plans for property development. Examples include plans for a shopping mall and a racetrack for horses, which might have resulted in farmers abandoning land due to expectations that the land would soon be expropriated. Municipal administrative staff noted that land tended to become abandoned either if the plots were too small or were not compatible with modern agricultural practices.

When asked about the opportunities for cultivating energy crops on abandoned cropland in the municipality, a key representative of the agricultural office in Malvik Municipality responded as follows (our translation):

> [The land tends to be] abandoned due to poor accessibility, topography, soil quality, drainage conditions, zoning, size, and so on. In other words, it tends to be land that it is not rational to use for the type of [modern] agricultural practices that have gradually emerged. I therefore have little faith that abandoned croplands in this municipality are interesting for the purpose of energy crops.
>
> (Interviewee 2)

Fourth, and finally, according to several of our interviewees, there are vast insecurities involved in starting to use an energy crop for which there is currently either a little or no known market, as well as nonexistent value chains for energy crops. These dynamics are frequently discussed in the literature as the "chicken and egg problem" (McCormick, 2011). As an agricultural adviser in the Trøndelag region clearly stated: "You need the farmers to grow something they can sell" (Interviewee 6). This points toward a policy potential, such as for public actors to establish and stimulate an early market for such crops based on pilot activities, as has been done for other niche technologies in the past (Ryghaug & Skjølsvold, 2021).

All interviewees highlighted that policy changes were needed to enable an energy crop niche in the Trøndelag region. Both farmers and authorities pointed to the need for financial support mechanisms as a central tool for stimulating the cultivation of new crops. They envisaged a multifaceted strategy whereby policies would experiment with targeting infrastructure developers, actors on the demand side such as biorefineries, as well as the actors regulating current markets for crops. Energy crop development activities are evidently highly context-specific, but also dependent on multi-scalar governance developments (Buck, 2018; Buck et al., 2020).

Interviewees reflected on the fact that there were no fundamental legal matters stopping farmers from switching to the production of energy crops, and that one could, for example, envision a future in which energy crop cultivation would become viable, primarily for farmers currently engaged in cultivating roughage (animal feed) intended for use in animal husbandry. Another interviewee (Interviewee 4) noted that a relevant experimental starting point could be to assess and articulate positive environmental co-benefits of bioenergy crop cultivation. Bioenergy crop cultivation could possibly be in "areas that lie along water and watercourses, where the grass can prevent erosion" (Interviewee 4). Interviewee 4 noted that in situations when farmers were considering switching to other forms of crops, there were also situations when a small amount of energy crops could improve soil quality. Most actors also acknowledged that an energy crop niche could be possible within the current and patchy land availability, but that this would require the formation and articulation of shared interests in this direction across diverse actors, combined with strong policy measures.

3.7. Recommendations for Further Modeling

Several key qualitative findings emerged that both complement and have major implications for insights provided by integrated assessment and biophysical modeling. First, whilst bioenergy expands rapidly in SSP-RCP2.6 land use projections in Norway, current local policies are not developed to establish a first bioenergy crop niche on abandoned cropland, and they do not support any large-scale bioenergy expansion at the modeled magnitude even beyond abandoned cropland. Second, land abandonment can be ephemeral and abandoned croplands follow mixed trajectories of recultivation for food/feed production, urban expansion, and continued natural regrowth. Third, recultivation for bioenergy production is highly unlikely without a strong policy push to guide recultivation from conventional agriculture to bioenergy. Moreover, recultivation has historically been a gradual process that has taken many years, and incentives have been necessary to achieve accelerated recultivation.

The following recommendations for further modeling of abandoned cropland recultivation for BECCS were formulated based on qualitative insights:

1. Previous resource-focused studies on mitigation potentials have assessed bioenergy recultivation as a "shock," with instant conversion of all areas to bioenergy production (Gvein et al., 2023; Næss et al., 2023). Temporal assessments are necessary to evaluate potential energy production and climate change mitigation over time, considering observed and potentially achievable recultivation rates.
2. Historically, continued regrowth has been considered a counterfactual benchmark to evaluate land-based mitigation opportunities arising from BECCS on abandoned cropland. However, an additional business-as-

usual scenario should reflect the historical recultivation trends for food/feed production, as recultivation threats have major implications for future aboveground carbon stocks and achieved mitigation.

3.8. Climate Change Mitigation Achieved Under Future Abandoned Cropland Trajectories

To provide a more nuanced assessment of energy and climate change mitigation potentials, we compared six explorative scenarios describing future pathways that abandoned cropland might follow depending on implemented policies. We evaluated our scenarios at the local, national, and global level.

3.8.1. Local and National Level

This section explores the effect of achievable recultivation rates on energy production, carbon fluxes, and achievable climate change mitigation at a local and national level.

At the local level (Trøndelag region), final energy production is in the range 0.14–0.23 PJ $year^{-1}$ for bioelectricity and 0.29–0.48 PJ $year^{-1}$ for FT diesel in 2030, depending on bioenergy recultivation pace (Figure 6a). By 2050, this increases to 0.39–0.56 PJ $year^{-1}$ and 0.81–1.2 PJ $year^{-1}$, respectively. For comparisons, the current final energy demand for land-based transport is 4 PJ $year^{-1}$ (mainly fossil fuels) in Trøndelag's largest city, Trondheim, which has about 45% of the regional population (Trondheim kommune, 2017).

With BECCS, CO_2 fluxes in Trøndelag are negative over time (considering supply chain emissions, land use change emission pulses, aboveground carbon accumulation through natural regrowth, and negative emissions from CCS) (Figure 6c), although only the bioelectricity conversion pathway achieves stronger annual mitigation than natural regrowth in 2050 through CCS (47%–106%, depending on recultivation pace). Cumulative negative emissions until 2050 become negligible for the food/feed recultivation scenario (0.0 $MtCO_2eq$), as aboveground carbon sequestration from natural regrowth is outweighed by reduced vegetational carbon due to recultivation for food/feed production (Figure 6e). Across the BECCS scenarios, negative emissions are 0.6 $MtCO_2eq$ to 2.5 $MtCO_2eq$, and only the bioelectricity conversion pathways can compete with the continued natural regrowth scenario (carbon sequestration of 2.3 $MtCO_2eq$). Evaluation of a longer period beyond 2050 would make BECCS bioelectricity increasingly preferable, due to a stronger carbon sink in 2050. Additional mitigation can be achieved through fossil energy substitution (Figure 6g). If fossil diesel is substituted with FT biodiesel, the achieved average mitigation over 2023–2050 becomes 79 $ktCO_2eq\ year^{-1}$ and 92 $ktCO_2eq\ year^{-1}$ with recultivation and accelerated recultivation, respectively. This is comparable with the average mitigation from bioelectricity conversion pathways with substitution of Norwegian grid electricity (78 $ktCO_2eq\ year^{-1}$ and 90 $ktCO_2eq\ year^{-1}$ with recultivation and accelerated recultivation, respectively), and negative emissions from continued regrowth (82 $ktCO_2eq\ year^{-1}$). However, if bioelectricity is exported to the European market, thereby replacing EU electricity grid mix or natural gas as a marginal generation technology, average mitigation could increase to 95–138 $ktCO_2eq\ year^{-1}$. Compared with annual road transport emissions in Trondheim (285 $ktCO_2eq\ year^{-1}$), average mitigation achieved in the BECCS scenarios with energy substitution were 27%–48% (Trondheim kommune, 2017).

The recultivation pace also influences the contribution that abandoned cropland can make to meet the bioenergy land use projections for Trøndelag. By 2030, 4.5 and 8.3 kha of abandoned cropland has been recultivated for bioenergy in the recultivation and accelerated recultivation for BECCS scenarios, respectively, equal to 5%–17% of projected bioenergy land use in 2030 in SSPx-RCP2.6 scenarios (Figure S7 in Supporting Information S1). Relative to modeling recultivation for bioenergy as an instant shock (Figure 4c), bioenergy land use in 2030 decreases by 60%–79%.

For Norway, final energy produced in 2050 is 0.8–2.6 PJ $year^{-1}$ across scenarios (Figure 6b). BECCS is generally a more competitive mitigation option relative to continued natural regrowth at the national average scale (Figures 6d and 6f), caused by poor conditions for natural regrowth in the northern parts of the country. Bioenergy crop yields are also lower in northern Norway than in Trøndelag, which may provide challenges for bioenergy recultivation. While Trøndelag contains only 28% of the Norwegian abandoned cropland, it has 43% of the energy potential and delivers 39%–42% of BECCS mitigation across comparable scenarios (2023–2050).

We found an average mitigation potential for Norway of 184–357 $ktCO_2eq\ year^{-1}$ across BECCS scenarios over the period 2023–2050 (Figure 6h), which is small relative to current Norwegian road transport emissions (8 $MtCO_2eq\ year^{-1}$) (Statistisk sentralbyrå, 2022). Achieved mitigation by 2050 under the accelerated

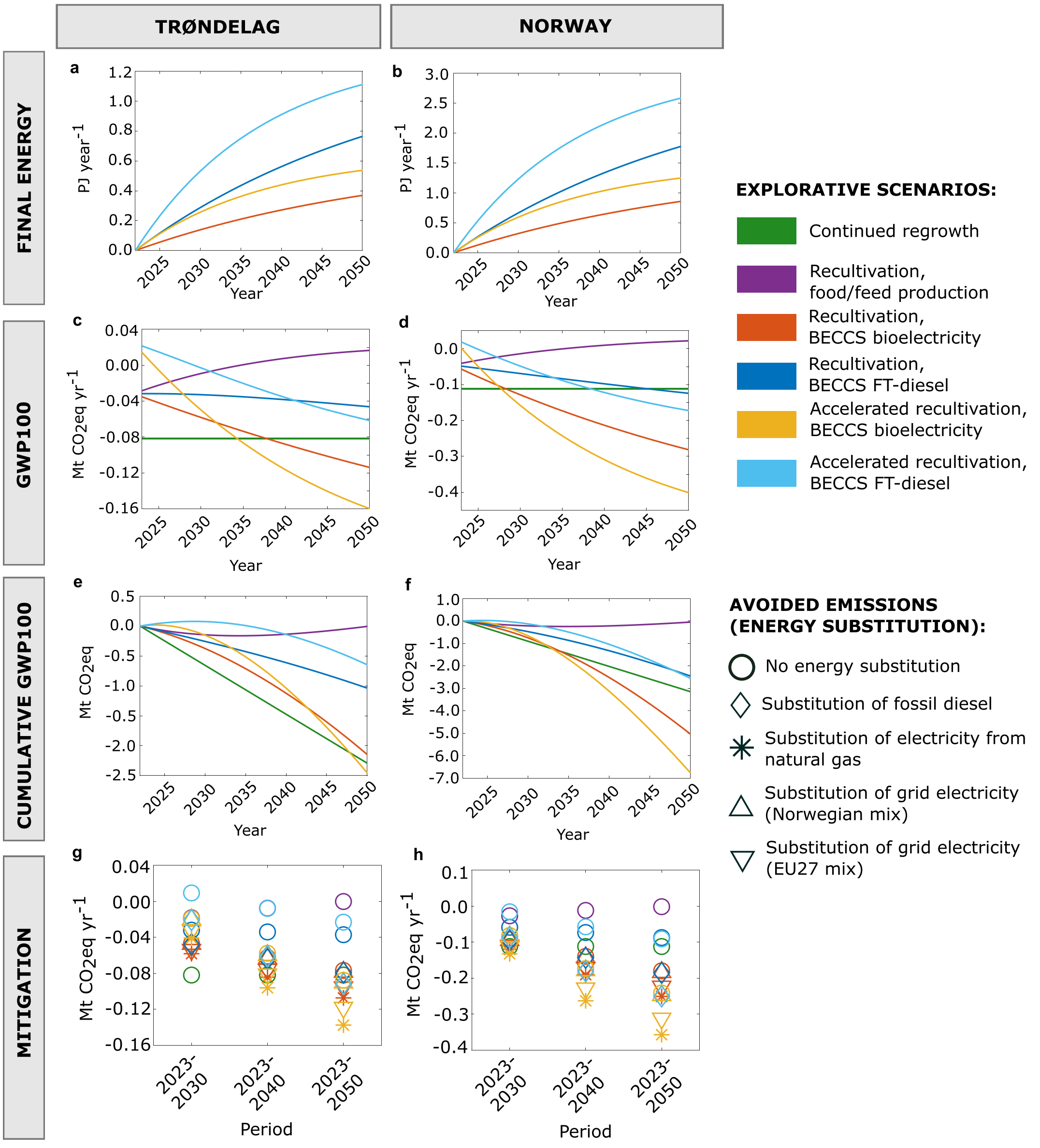

Figure 6. Final energy, climate change impacts, cumulative climate change impacts and achieved climate change mitigation for different explorative scenarios of abandoned cropland trajectories. (a, b) Final energy produced per year over time (joule year^{-1}). (c, d) Climate change impacts (CO$_2$eq year^{-1}) caused by activities each year, considering natural regrowth, land use change, supply chain, and carbon capture and storage (CCS). (e, f) Cumulative climate change impacts due to carbon emissions/sequestration over time (CO$_2$eq) considering natural regrowth, land use change, supply chain, and CCS. (g, h) Average climate change mitigation (CO$_2$eq year^{-1}) achieved over different periods (2023–2030, 2023–2040, and 2023–2050) due to natural regrowth, land use change, CCS, and potentially avoided emissions. Parts (a, c, e, and g) refer to Trøndelag, and parts (b, d, f, and h) to Norway. Colors indicate the explorative scenarios. Markers describe the considered energy carrier used to calculate avoided emissions from energy substitution in mitigation results. Avoided emissions are only considered in parts (g and h). It should be noted that different scales are used on *y*-axis of the different parts in the same rows.

recultivation for the BECCS bioelectricity scenario is about 50% of our initial estimate with instant land use conversion. Achievable recultivation rates are therefore of vital importance to mitigation estimates.

3.8.2. Global Level

When the explorative scenarios are applied at a global scale, the global production of FT biofuels is 3.0 and 5.6 EJ year^{-1} in 2030 and increases to 8.1 and 11.8 EJ year^{-1} in 2050 for the BECCS FT-biofuels recultivation

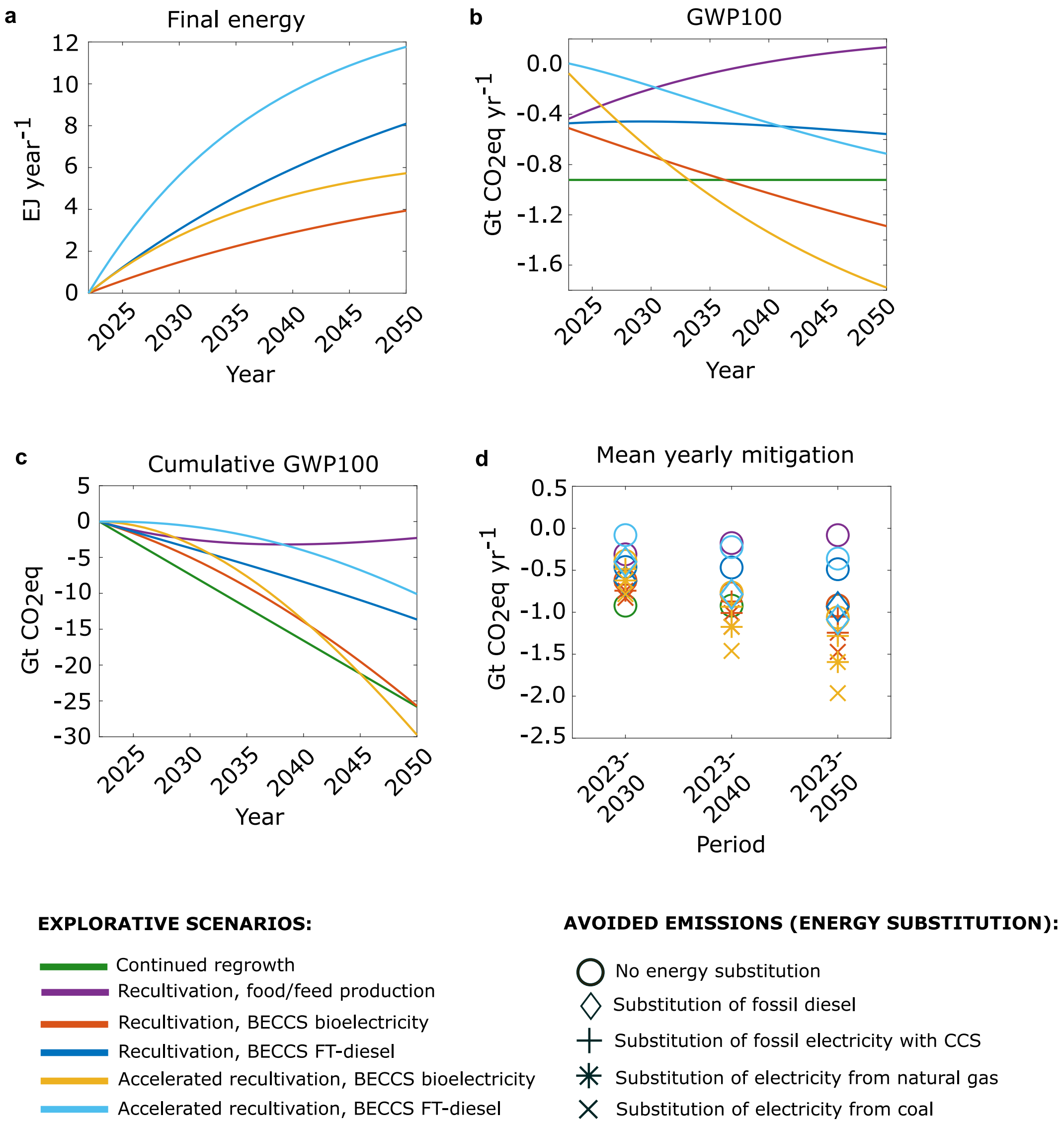

Figure 7. Globally achieved final energy, climate change impacts, cumulative climate change impacts, and climate change mitigation for different explorative scenarios of abandoned cropland trajectories. (a) Final energy produced per year over time (EJ year^{-1}). (b) Climate change impacts (CO_2eq year^{-1}) caused by activities each year, considering natural regrowth, land use change, supply chain emissions, and carbon capture and storage (CCS). (c) Cumulative climate change impacts over time due to natural regrowth, land use change, supply chain activities, and CCS (CO_2eq). (d) Average climate change mitigation (CO_2eq year^{-1}) achieved over different evaluation periods (2023–2030, 2023–2040, and 2023–2050) considering natural regrowth, land use change, supply chain activities, CCS, and potentially avoided emissions. Colors indicate the explorative scenarios. Markers describe the considered energy carrier used to calculate avoided emissions from energy substitution in mitigation results. Avoided emissions is only considered in part (d).

and the accelerated recultivation scenarios, respectively (Figure 7a). This corresponds to 30%–130% and 23%–85% of the median global liquid biofuel supply in 2030 and 2050, respectively, across SSP-RCP2.6 scenarios from multiple IAMs (Riahi et al., 2017; Rogelj et al., 2018). For the bioelectricity scenarios, final energy production is lower (1.5–2.7 EJ year^{-1} and 3.9–5.7 EJ year^{-1} in 2030 and 2050, respectively, depending on recultivation pace), but still sufficient to support production increase in line with median projected future bioelectricity supply across SSP-RCP2.6 scenarios (31%–157% and 13%–62% of supply in 2030 and 2050, respectively) (Riahi et al., 2017; Rogelj et al., 2018). Our comparison was done with cross-model medians that differs from the GCAM land use projections shown in Figure S5 in Supporting Information S1, and there are large cross-model variations (Bauer et al., 2020; Daioglou et al., 2020).

Currently, aboveground carbon stocks on abandoned cropland are increasing (0.4 $GtCO_2eq$ $year^{-1}$ sequestered (Figure 7b)) in our business-as-usual scenario (recultivation for food and feed production), as continued natural regrowth is the dominant process. This continues until 2039, before becoming a net source of emissions as continued recultivation for food and feed production becomes a more dominant process than regrowth. In 2050, land clearance of previously accumulated vegetation carbon leads to net annual emissions of 0.1 $GtCO_2eq$ $year^{-1}$. With strict and successful regulations to avoid recultivation, continued natural regrowth everywhere would deliver mitigation of 0.9 $GtCO_2eq$ $year^{-1}$ on average, and instead act as a stable carbon sink. Considering recultivation for BECCS, and excluding the benefits of fossil energy substitution, CO_2 fluxes are predominantly negative over the period across scenarios. However, only the bioelectricity conversion pathway delivers larger annual net negative emissions in 2050 than the continued natural regrowth scenario, mainly due to the higher carbon capture efficiency. With accelerated recultivation for BECCS bioelectricity (11 years half-life), the annual carbon sink is about twice as strong as under continued natural regrowth by 2050.

Over the 2023–2050 period, abandoned cropland is a weak carbon sink under the recultivation for food/feed production scenario (1.8 $GtCO_2eq$ sequestered) (Figure 7c). Continued natural regrowth delivers 89% and 155% larger mitigation than the recultivation and accelerated recultivation scenarios for BECCS FT-diesel, respectively (excluding avoided emissions of fossil fuel). BECCS bioelectricity performs equally to natural regrowth under the recultivation scenario, and stronger with accelerated recultivation (+15% mitigation, mainly due to CCS). Fossil energy substitution is key to maximize the climate benefits of BECCS (Figure 7d), and considering substitution of fossil diesel, the BECCS FT-diesel scenarios achieve stronger mitigation until 2050 than continued regrowth (+1% and +18% for recultivation and accelerated recultivation, respectively). BECCS bioelectricity with substitution of fossil-based electricity achieves average annual mitigation of 1.1–2.0 $GtCO_2eq$ $year^{-1}$, which is 14%–113% higher than natural regrowth, and with high-end estimates relying on accelerated recultivation and substitution of coal electricity. Achieved average mitigation from continued regrowth and the BECCS recultivation scenarios equals 2%–5% of annual global anthropogenic CO_2 emissions in 2021. Relative to modeling bioenergy recultivation as a "shock" with instant land use change (Figure S5 in Supporting Information S1), the achieved mitigation is 47%–61% lower with gradual recultivation. This highlights an important trade-off, as a delayed BECCS recultivation typically leads to lower climate benefits over the evaluation period and reduces carbon sinks and avoided emissions in 2050.

3.9. Limitations of Study

Our findings are affected by multiple uncertainties and limitations arising from the integration of different data sets and methods (see also Text S4 in Supporting Information S1). Challenges can arise when integrating qualitative and quantitative data due to the different research paradigms where the researcher has different ontological and epistemological orientations (Archibald, 2016). All authors of this paper were aware of this risk, and we were humble and open to making the collaboration work and not going down the rabbit hole of controversies that exist when using mixing methods (Creswell, 2011). Our approach can be placed in the paradigms of critical realism (Sovacool et al., 2018).

Field observations have shown that short-rotation woody bioenergy crops may provide superior yields relative to perennial grasses in parts of the globe (W. Li et al., 2018, 2020). Especially, for Norway, willow and poplar are key candidate woody crops (W. Li et al., 2020; Mola-Yudego et al., 2016). In general, we expect that the inclusion of woody bioenergy crops in this study would lead to higher BECCS potentials with a yield-optimal crop distribution, but not affect our main conclusions. Uncertainties may also arise from varying yield predictions across models. While we used GAEZ and focused on perennial grasses, GCAM considers both perennial grasses and short-rotation woody crops for dedicated bioenergy production (Chen et al., 2020a).

Future land use projections are heavily dependent on assumed socio-economic development, such as population change, agricultural intensification, dietary consumption patterns, land-use regulations, and trade (Stehfest et al., 2019). For GCAM, bioenergy deployment is determined by information exchanges between individual modeling components such as the land (including yield modeling and biomass supply), water (irrigation), energy (technological performance, supply chains), socioeconomic conditions, and climate (Calvin et al., 2019), each with their own associated uncertainties. Specifically, the climate forcing used by the GCAM Demeter framework can lead to uncertainty ranges (maximum minus the minimum) up to 10% for certain land types (Chen et al., 2020a). The massive bioenergy expansion seen in GCAM SSP-RCP2.6 scenarios downscaled with Demeter for Norway may indicate that the model has unresolved challenges in this region. We chose to utilize these land use projections here despite this as it represents the highest resolution and most comprehensive attempt at modeling future global land use to date.

Norway was used as a local case-study for the qualitative analysis, which represents a limitation as there might be country-specific socioeconomic features present that does not translate to other regions that show intensive cropland abandonment. Follow up studies should consider addressing a bioenergy recultivation in other regions.

We did not consider future energy system decarbonization. The use of prospective LCA-inventories could have allowed better capturing the effects of future technological change (Sacchi et al., 2022). Likewise, the sensitivity of crop yields to global warming was not considered. A previous study showed that global bioenergy potentials on abandoned cropland decreased by −2% and −6% by 2050, under RCP4.5 and RCP8.5, respectively, but also that the yields of perennial grasses at high latitudes (such as in Norway) are expected to increase (Næss et al., 2021).

Biophysical feedback from land use change not considered here may also affect the regional climate. Relative to cropland, bioenergy crops are typically associated with a biogeophysical cooling effect that can enhance the effectiveness of BECCS in limiting global temperature increase (Wang et al., 2021, 2023), although effects are heterogenic (Melnikova et al., 2023; Muri, 2018). Biogeophysical effects caused by reforestation due to changing albedo and land evapotranspiration are likewise important. At lower latitudes, tropical reforestation is typically linked with a biogeophysical cooling effect, whilst for higher latitudes, such as for Norway's boreal forests, reforestation warms the local winter climate (Windisch et al., 2021).

4. Concluding Discussions

BECCS is essential in most climate change mitigation scenarios that limit global warming to below 2°C (Rogelj et al., 2018), and targeting abandoned croplands has frequently been highlighted as a promising sustainable near-term opportunity. Due to the complexity of the biosphere and the anthroposphere, bioenergy resource potentials can only be modeled and not measured (Slade et al., 2014). Our qualitative analysis suggest that the realization of the modeled bioenergy resource potential seems unlikely without major policy changes. In Norway, current policies, farming practices, markets, established understandings of abandoned land, and ways of dealing with such land all suggest that current agricultural regimes are strong with respect to land use and crop cultivation. Current agricultural innovation and energy transition activities point in different directions, such as the establishment of new modes of heating and electrification. Hence, the establishment of a first energy crop niche comes across as a daunting task. We question the degree to which much of the abandoned land identified through remote sensing in the studied region (Trøndelag) could be characterized as abandoned if subject to further scrutiny. Instead, the land in question has tended to be understood as part of a reservoir of land that should, and in many instances will, be remobilized for food crops or as grazing lands. This aligns with other recent local-level findings suggesting that more than half of the land that is abandoned will be recultivated for food production within the first 30 years following abandonment (Crawford et al., 2022). We thus highlight a major challenge associated with bioenergy resource modeling, as remote-sensing techniques alone cannot capture actual land availability for land-based climate change mitigation strategies. This also points to the need to revisit the typical modeler's assumption that future land abandonment will make land available for energy crops, as commonly applied in future projections of bioenergy supply and demand (Daioglou et al., 2019; Doelman et al., 2018; Köberle, 2019).

We have illustrated a substantial gap between the pace of bioenergy crop expansion found in land use projections in stringent climate change mitigation scenarios, the modeled bioenergy resource potentials that could theoretically be sustainably deployed in the near-term to ramp-up supply, and the feasibility of actual realization of these in the real world from the local Norwegian level, based on sociotechnical analysis. This highlights the untapped potential of bringing in increased local and sociocultural detail in the broad assumptions that make up large-scale modeling exercises. Improved global-local knowledge exchanges can also help inform local policymakers and stakeholders of how local actions may contribute to achieve global sustainability goals.

By combining quantitative and qualitative findings, we designed a set of explorative scenarios that provided new insights into the complex dynamics of abandoned cropland as a land-based climate change mitigation option that complements previous resource-focused studies. A key finding is that ongoing recultivation trends for food/feed production risks making climate change mitigation from natural regrowth on our mapped abandoned cropland over a 30-year evaluation period almost negligible. We have shown that if recultivation for BECCS is modeled as a gradual process based on historical recultivation rates, the achieved 30-year climate change mitigation is approximately halved relative to a resource-focused approach that models land use change for BECCS as an instant shock. Delaying a BECCS recultivation of abandoned cropland will make it impossible to reach high-end mitigation potentials, and an accelerated BECCS recultivation is needed to ensure stronger mitigation.

New policies are needed to prevent recultivation or to divert ongoing recultivation towards biomass production for BECCS if recently abandoned cropland is to deliver a meaningful contribution to climate change mitigation. Our mixed-methods approach and the results from it serve as strong reminders of the limitation of individual disciplines, theories, and methods, both as a way of describing the world, and as a mode for producing actionable knowledge.

Data Availability Statement

Data supporting the findings of this study has been made available online (Næss et al., 2024a). Custom code is available at Zenodo (Næss et al., 2024b). GAEZ v4 biomass yields are available from FAO (2022), global gridded land use projections from Chen et al. (2020b), ESA CCI land cover data at Copernicus Climate Change Service, Climate Data Store (2019), and natural regrowth data from Cook-Patton et al. (2020b).

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