

Potentials and barriers to land-based mitigation technologies and practices (LMTs)—a review

Karki, Lokendra; Lieu, Jenny; Xylia, Maria; Laub, Moritz; Ismangil, David; Virla, Luis; Rahn, Eric; Bilbao, Bibiana Alejandra; Indriani, Siti Nurlaila; More Authors

DOI

[10.1088/1748-9326/ace91f](https://doi.org/10.1088/1748-9326/ace91f)

Publication date

2023

Document Version

Final published version

Published in

Environmental Research Letters

Citation (APA)

Karki, L., Lieu, J., Xylia, M., Laub, M., Ismangil, D., Virla, L., Rahn, E., Bilbao, B. A., Indriani, S. N., & More Authors (2023). Potentials and barriers to land-based mitigation technologies and practices (LMTs)—a review. *Environmental Research Letters*, 18(9), Article 093003. <https://doi.org/10.1088/1748-9326/ace91f>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

TOPICAL REVIEW • OPEN ACCESS

Potentials and barriers to land-based mitigation technologies and practices (LMTs)—a review

To cite this article: Lokendra Karki *et al* 2023 *Environ. Res. Lett.* **18** 093003

View the [article online](#) for updates and enhancements.

You may also like

- [First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole](#)
The Event Horizon Telescope Collaboration, Kazunori Akiyama, Anton Alberdi et al.
- [First Sagittarius A* Event Horizon Telescope Results. II. EHT and Multiwavelength Observations, Data Processing, and Calibration](#)
Event Horizon Telescope Collaboration, Kazunori Akiyama, Anton Alberdi et al.
- [First M87 Event Horizon Telescope Results. III. Data Processing and Calibration](#)
The Event Horizon Telescope Collaboration, Kazunori Akiyama, Anton Alberdi et al.



Breath Biopsy[®] OMNI[®]

The most advanced, complete solution for global breath biomarker analysis

TRANSFORM YOUR RESEARCH WORKFLOW



Expert Study Design & Management



Robust Breath Collection



Reliable Sample Processing & Analysis



In-depth Data Analysis



Specialist Data Interpretation

ENVIRONMENTAL RESEARCH LETTERS



TOPICAL REVIEW

OPEN ACCESS

RECEIVED
13 February 2023

REVISED
20 June 2023

ACCEPTED FOR PUBLICATION
13 July 2023

PUBLISHED
14 September 2023

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Potentials and barriers to land-based mitigation technologies and practices (LMTs)—a review

Lokendra Karki^{1,*}, Jenny Lieu², Maria Xylia³, Moritz Laub⁴, David Ismangil², Luis Virla², Eric Rahn⁵, Bibiana Alejandra Bilbao^{6,7,16}, Siti Nurlaila Indriani⁸, Pilar Martin Gallego⁹, Afnan Khalil Ahmad Suleiman¹⁰, Ruediger Schaldach¹¹, Takeshi Takama⁸, José Rafael Marques da Silva^{12,13,14} and Francis X Johnson¹⁵

- ¹ Science Policy Research Unit (SPRU), University of Sussex, Jubilee Building, Brighton BN1 9SL, United Kingdom
- ² Delft University of Technology (TU Delft), Multi-Actor Systems Department Building 31, Jaffalaan 5, 2628 BX Delft, The Netherlands
- ³ Stockholm Environment Institute, Linnégatan 87D, 115 23 Stockholm, Sweden
- ⁴ Department of Environmental Systems Science, ETH Zurich, Universitätsstrasse 2, Zürich, Switzerland
- ⁵ International Center for Tropical Agriculture (CIAT), Km 17 recta Cali-Palmira, Cali, Colombia
- ⁶ Department of Environmental Studies, Simón Bolívar University, Apartado 89000, Caracas 1080A, Venezuela
- ⁷ COBRA Collective, 21 Willson Road, Englefield Green, Surrey TW20 0QB, United Kingdom
- ⁸ Sustainability and Resilience (su-re.co), Jl. Dalem Gede No.25, Pererenan, Kec. Mengwi, Badung, Bali 80351, Indonesia
- ⁹ Ambienta Ingeniería y Servicios Agrarios y Forestales, Pl. Constitución, 2, 10810 Montehermoso, Cáceres, Spain
- ¹⁰ Bioclear earth, Rozenburglaan 13, Groningen 9727 DL, The Netherlands
- ¹¹ Center for Environmental Systems Research (CESR), University of Kassel, Wilhelmshoer Allee 47, 34119 Kassel, Germany
- ¹² Agroinsider, Rua Circular Norte, Edifício NERE Sala 12.10, 7005-841 Évora, Portugal
- ¹³ University of Évora, Largo dos Colegiais 2, 7004-516 Évora, Portugal
- ¹⁴ MED—Environmental and Agriculture Research Cente, Herdade da Mitra, Valverde, 7000 Évora, Portugal
- ¹⁵ Stockholm Environment Institute, SEI-Asia, 254 Chulalongkorn University, Henri Dunant Road, Pathumwan, Bangkok 10330, Thailand
- ¹⁶ Montpellier Advanced Knowledge Institute on Transitions (MAK'IT), Université de Montpellier, 163 rue Auguste Broussonnet, Montpellier 34090, France

* Author to whom any correspondence should be addressed.

E-mail: L.Karki@sussex.ac.uk

Keywords: land-based mitigation technologies, LMT, sustainability, barriers, potentials

Abstract

Land-based mitigation technologies and practices (LMTs) are critical for achieving the Paris Agreement's aim of avoiding dangerous climate change by limiting the rise in average global surface temperatures. We developed a detailed two-level classification and analysis of the barriers to the adoption and scaling up of LMTs. The review suggests that afforestation/reforestation and forest management are LMTs with wide application and high potential across all continents. BECCS (bioenergy with carbon capture and storage) and biochar have a higher potential in higher-income countries in the short term, due to the availability of technology, funding, and low-cost biomass value chains. Although most LMTs can be cost-effective across multiple world regions, limited knowledge concerning their implementation and insufficient financing appear to be the main barriers to their large-scale deployment. Without considering gender and the rights of marginalised and Indigenous Peoples, the large-scale deployment of LMTs can further aggravate existing inequalities. Therefore, the social and institutional implications of LMTs need to be better understood to improve their public acceptance and reduce negative impacts. An integrated system approach is necessary to strike a balance between ambitious land-based mitigation targets and socioeconomic and environmental goals.

1. Introduction

In recent years, there has been significantly increased policy and academic interest in understanding the potential contribution of land-based mitigation technologies and practices (LMTs) for climate

change mitigation. The Intergovernmental Panel on Climate Change (IPCC) reports prepared during the 6th assessment cycle including the 'SR1.5 report' (IPCC 2018), the 'Climate Change and Land Report' (IPCC 2019), and the 'WGIII Report' (IPCC 2022) emphasised the vital need for sustainable use

and management of land to combat climate change and to maintain land productivity to increase, food security and biodiversity. The growing likelihood of reliance on the land for climate change mitigation is due to the slow pace of emissions reductions, which has led to greater demand for carbon sequestration in order to achieve the climate targets (Grassi *et al* 2021).

The agriculture, forestry and other land use (AFOLU) sector accounts for nearly a quarter (23%) of anthropogenic greenhouse gas (GHG) emissions (IPCC 2019). This sector is second only to the energy sector for GHG emissions. Notably, land absorbs nearly a third (30%) of the GHG emissions in the atmosphere and this volume can be increased by appropriate interventions (Duffy *et al* 2021). Therefore, LMTs in the AFOLU sector are deemed critical for determining climate-resilient pathways and contributing to adaptations to achieve social and environmental sustainability, for meeting the primary objective of the Paris Agreement, which is to limit global temperature rises to well below two degrees Celsius.

Land based mitigation technologies and practices (LMTs) is also known as 'land-based climate change mitigation measures' (Frank *et al* 2021, Roe *et al* 2021, Fujimori *et al* 2022) or AFOLU mitigation (IPCC 2014), but an explicit definition is still lacking. We define LMTs as *deliberate human actions aimed at reducing the GHG emissions from land use and removing GHGs from the atmosphere by utilising land as a carbon sink, which together provide environmental and social co-benefits*. LMTs can involve trade-offs, such as albedo changes, loss of biodiversity, and competition for land (OECD 2020, Shin *et al* 2022, Vera *et al* 2022). This definition is adapted from IPCC reports (IPCC 2014, 2019, 2022), which describe climate mitigation as human interventions for reducing sources or increasing sinks of GHGs. For discussions of different human actions to respond to climate change, set out in IPCC documents, see Minx *et al* (2018).

Our definition of LMT includes 'practices', understood as dynamic and proactive human interventions, aimed at reducing emissions and increasing the removal of carbon from the atmosphere. Rather than referring to negative emission technologies (NETs) or carbon dioxide removal (CDR) from the atmosphere, LMT is a broader term that emphasises changes to land use and land management to reduce emissions and increase carbon sequestration, which excludes practices with strong trade-offs. It covers various terms, including 'nature-climate solutions', 'low carbon agriculture' and 'carbon farming'. Our study focuses mainly on rural areas, park land and other managed land outside of city boundaries. We do not include nature-based solutions (NBS) that are applied in cities, but this does not preclude future work from considering NBS as LMT. In our study, we emphasise that LMTs should optimise mitigation

and adaptation objectives and take account of local resources and broader positive environmental and social sustainability.

The possible contribution of land to climate change mitigation has been discussed in climate negotiations since the 1992 Kyoto Protocol Agreement (Carton *et al* 2020). The study of different land use practices, including forest management, agroforestry, reduced tillage and organic farming, has a long history. While there is a large body of research on the potential of land for carbon sequestration or emission reductions (e.g. (Lal 1999, 2004)), it was only quite recently that these land use practices began to be seen as critical climate mitigation tools, for example, the French Government's 4 per 1000 initiative, launched in 2015 at the COP21 conference (Minasny *et al* 2017, Rumpel *et al* 2022). The gradual shift in the focus on carbon in land is based, also, on different stakeholders' expectations of multiple co-benefits, including improved nutrient cycling, biodiversity conservation, reduced soil erosion and improved water quality (Kim *et al* 2008, Bashir *et al* 2019). The increased research attention to these issues is being accompanied by increased debate around the potential, uncertainties and effectiveness of LMTs due to the need to find synergies and understand the trade-offs among different social, economic and environmental goals.

Understanding the potential of various LMTs is critical to the climate policy decision-making process, which requires a broader approach than viewing LMTs from a conventional techno-economic viewpoint. Extant research, which tends to focus on understanding LMTs based on techno-economic modelling of one or few LMTs, does not provide a comprehensive understanding of the mitigation potential in the land use sector where different non-technical barriers constrain deployment of LMTs. Also, we have limited comprehensive research on the potentials and barriers across a wider portfolio of LMTs. We build on previous works on mitigation technologies or NETs (Fuss *et al* 2018, Minx *et al* 2018, Cobo *et al* 2023). The aforementioned studies encompass findings from both bottom-up studies and top-down analyses. However, there is a need for a comprehensive methodological analysis that integrates these approaches. Currently, bottom-up studies are isolated from each other, often overlooking the interconnections between LMTs within portfolios. While these studies discuss LMTs, they frequently neglect to address the practical implementation barriers and challenges associated with scaling them up.

We analyse potentials of LMTs and develop a detailed two-level classification and analysis of the barriers to adoption and scaling-up of LMTs. Section 1 discusses the concept and the importance of LMT; section 2 describes the methodology; section 3 provides a brief overview of their technical and economic potential; section 4 explores the main

barriers; section 5 comprises discussion of main findings and conclusions in section 6.

2. Methodology

Our methodology protocol involved expert and stakeholders' knowledge in combination with literature review to understand potentials and barriers of LMT deployment. The review team was comprised of an international team of interdisciplinary experts who explored different LMTs in their respective regions and countries. The literature review contributed to our methodology which draws explicitly on empirical knowledge held by case study experts from disciplines including social sciences, forestry, agricultural sciences, computer modelling and engineering. In addition, the literature review covers work produced in five different languages—English, German, Spanish, Portuguese and Indonesian, which broadens the scope considerably. The case study leaders also consulted stakeholders in their networks, to guide the review process and to provide additional insights and sources. Thus, the literature review does not depend on use of a specific scientific search engine selecting the most frequently cited papers relevant to the research community; rather it is based on the embedded and situated knowledge of experts, which means that it includes work published on the world wide web or by local language resource centre (i.e. on-line resources or books).

Each expert groups identified relevant sources related to the potentials and barriers of LMTs within or outside their regions. The aim was to identify sources that provided insights relevant for farmers, land use managers and policy makers, or those involved in decision making about the implementation of LMTs, rather than identifying literature with scientific significance (i.e. the most frequently cited scientific articles). We developed a search protocol which consisted search strings containing LMTs (e.g. 'name of the LMT' with 'economic mitigation potential', 'technical mitigation potential', 'barriers', 'constraints', 'challenges', 'emission reduction', 'carbon sequestration', 'carbon removal') which were adapted to different LMTs and countries, regions and the main research directions. Alternative names of the LMTs were also used. For example, in the case of the reduced tillage LMT, we included minimum tillage, zero tillage, conservation tillage, along with their abbreviations.

We set out exclusion and inclusion criteria for the review process. The selected articles should have covered at least one of the LMTs included in this paper and specifically focused on selecting the papers with barriers to LMT deployment. For papers related to technical mitigation potential, we selected publications with global level information. We excluded the literature on technical potential of LMTs at a small

scale (e.g. per unit land area, sub-regional area, and national level), but included the paper, if it contained barriers of LMT implementation. In order to select papers on the economic potential of LMTs, we included papers discussing economic potential, covering the country or region. Based on the exclusion inclusion criteria, abstracts were reviewed prior to the full review of articles. Drawing on stakeholders' knowledge and the international team members' expertise, we constructed an initial list of 649 publications. After careful screening, the list was reduced to 346 publications.

Among 346 publications, including reports and other materials, 307 were published between 2010 and 2022. Literature was sourced using available Google search engines, in order to include non-academic journals, and Scopus, the Web of Science and Google Scholar were used to identify academic literature. We also consulted local government and industry association websites. There was a significant increase in the literature on LMTs after 2015. Among our later sample of 346 publications, 246 are academic journal articles and 22 are books. The grey literature reviewed consists of 64 reports (NGO, government and other), 4 bulletins, 8 websites and 21 other sources (e.g. theses, guidelines, and datasets). The different aspects of climate and environmental science are represented based on the disciplines covered in the literature review; most articles are from the ecology and agricultural sciences, geography, biogeochemistry and biology fields. Papers on agriculture and economics were classified as agricultural sciences. In the cases where LMTs were not well covered by existing academic literature or were not in English, we considered grey literature to fill in some of the gaps, including new and upcoming policies. Data extraction was focused on (i) area coverage and growth of LMT in the case study countries and regions (ii) technical potential (iii) economic potential (iv) barriers.

A bibliometric mapping of our sample of 346 scientific publications is shown in figure 1. We identified the 59 most frequently mentioned terms and using VOSViewer software (Van Eck and Waltman 2010), we constructed seven clusters based on keyword co-occurrence. Their size is represented by the different sized circles. The main categories refer to carbon capture and storage (pink), bioenergy (purple), negative emissions (orange), bio-energy with carbon capture and storage (BECCS) (yellow), climate change mitigation (green), biomass resources (red) and global climate change (teal).

The resulting network shows that most of the scientific research on LMTs has focused on land use to address energy, emissions, and climate change issues. However, a focus on implementation and barriers has been absent in most research scopes in the past decades, as it is only related to 'uncertainty analysis', shown as a small cluster. Figure 1 shows

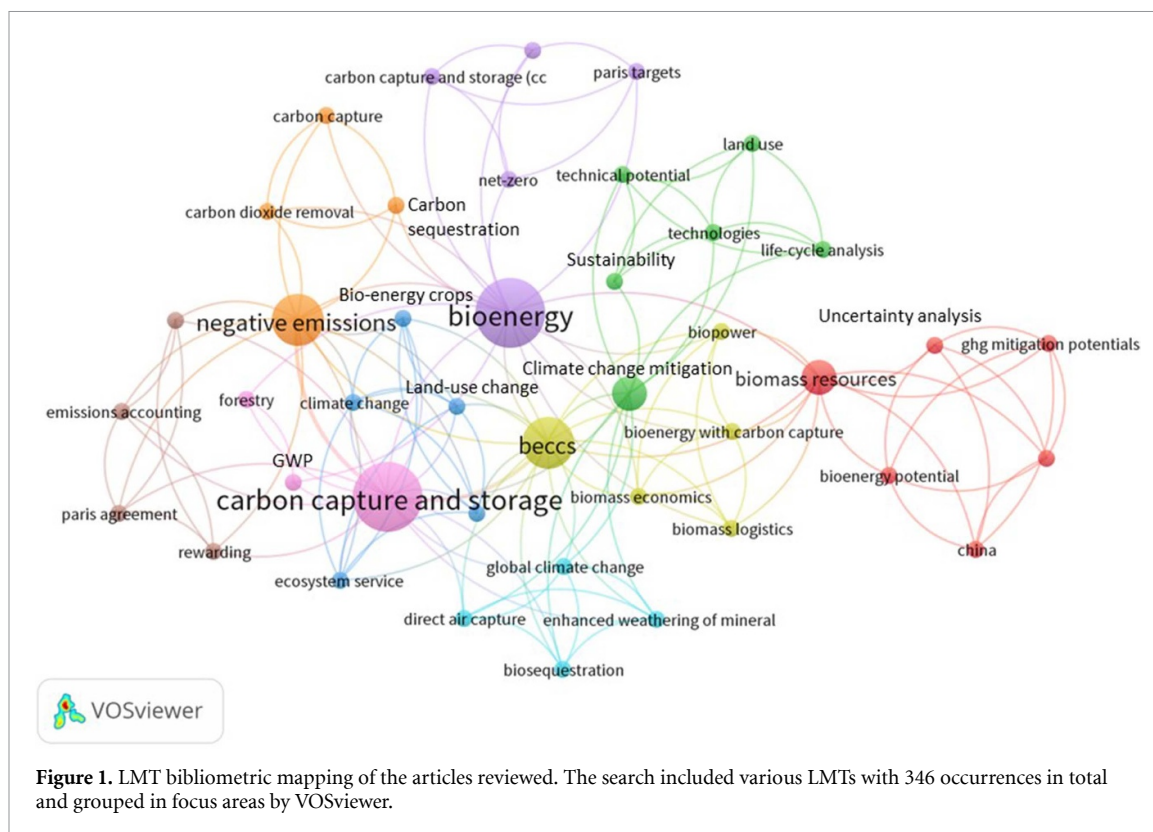


Figure 1. LMT bibliometric mapping of the articles reviewed. The search included various LMTs with 346 occurrences in total and grouped in focus areas by VOSviewer.

the interconnectivity across LMTs and reinforces the need to consider portfolio of LMTs rather than a single technology or practice. We consider 13 LMTs in the 5 categories of agriculture, forestry, bioenergy, biogenic waste management and other ecosystems (table 1).

3. How much mitigation potential do the LMTs have?

Among existing literature, estimations of the mitigation potential of LMTs vary widely. An early study by Dixon (1995) found that land resources management can mitigate around 10%–40% (0.7–2.8 Gt C year⁻¹) of total GHG emissions. In general, studies conducted at the global scale prior to the publication of the IPCC AR5 reports in 2013–2014, show modest total mitigation potential of land-use (<10 Gt CO₂ e year⁻¹). Smith *et al* (2013) argue that supply-side land based mitigation solutions could offset around 1.5–4.3 Gt CO₂ e year⁻¹ at a carbon price of 20–100 US\$ t CO₂ e year⁻¹.

More recent studies suggest that LMTs have higher potential. The chapter on AFOLU in the IPCC AR5 report suggests mitigation potential of 7.2–10.6 Gt CO₂ e year⁻¹ (Smith *et al* 2013) and in the AR6 report (IPCC 2022), this increases slightly to 8–14 Gt CO₂ e year⁻¹. The estimates in Roe *et al* (2019, 2021) are even higher at 13–15 Gt CO₂ e year⁻¹. Among estimates of the potential contribution from the land-use sector, Griscom *et al* (2017) suggests that it could be upto 23.8 Gt CO₂ e year⁻¹

and argues that prior studies did not estimate the full potential contribution of land-based mitigation.

These large variations in the potential of LMTs are due to methodological differences, mainly datasets, assumptions and models employed (IPCC 2019, 2022). Therefore, accurate assessment of climate mitigation related to the AFOLU sector still seems difficult (Roe *et al* 2021). In this study, we do not go into detail about the different approaches used in the studies reviewed. However, as the number of studies and detailed assessments increase, this would be an interesting future research direction. We can hypothesise that an essential factor affecting these estimates is their timing with some earlier assessments underestimating the potential of new technology. As the technology develops, they lead to an improved technical and economic potential increase. Also, the effectiveness of the various LMT depends on sustainability targets (Fuss *et al* 2018), which could affect upper and lower estimates.

Table 2 presents estimates for the potential of each selected LMT, on a global scale. Figure 2 depicts the LMT portfolio at the continental level. Afforestation and reforestation (AR), forest management, agroforestry, BECCS and biochar are the LMTs with the largest mitigation potential. The potential for improved rice cultivation is limited mainly to Asia. The largest potential for land-based mitigations is in Asia, South America and Europe. The literature is skewed towards LMTs with large potential at a global scale. So far, there is an absence of detailed global studies on LMT with lower mitigation

Table 1. Description of LMTs considered in this study and potential for emission reduction and carbon removal.

Category	LMT	Description	Emission reduction	CO ₂ removal	Main co-benefits	Main trade-offs	References
Agriculture	Agroforestry	Trees integrated with crops, livestock or both on the same piece of land.	✓	✓	Higher soil functionality Higher system productivity	Increased labour requirement Reduced yield of the main crop.	(Mosquera-Losada et al 2018, Nair et al 2021 van Noordwijk 2018)
	Direct dry seeded rice	Rice seeds sown directly by drilling the soil, instead of transplanting seedlings.	✓	✓	Increases soil functions, reduces use of water and labour.	High weed pressure	(Mahajan et al 2013, Sapkota et al 2017, Wang et al 2017, Laing et al 2018, Dhaliwal et al 2020)
	Reduced tillage	Reducing disturbance to the soil during crop cultivation by reducing inversion tillage.	✓	✓	Lower fuel requirement	Higher weed pressure	(Lahmar 2010, Soane et al 2012, Lal 2013)
	Integrated soil fertility management	A farming method that integrates application of chemical fertilisers, organic matter inputs and improved plant varieties to maximise agronomic efficiency of nutrients.	✓	✓	Higher yields More efficient nutrient cycling	Sourcing of external inputs in competition with other lands	(Chivenge et al 2009, Adolwa et al 2019a, Gram et al 2020 Wawire et al 2021)
	Organic agriculture	A farming system where inputs include animal manure, compost and leguminous plants and avoids use of synthetic fertiliser and pesticides.	✓	✓	More efficient nutrient cycling Fewer inputs	Possible lower yields	(Leifeld and Fuhrer 2010, Seufert et al 2012, Meng et al 2017, Smith et al 2019a, Gong et al 2022)
	Biochar	An organic material produced from burning biomass in a high temperature, pyrolysis process.	✓	✓	Buffers soil pH Improves soil stability and structure. Improved soil fertility co-products for the energy and livestock sectors.	Unwanted creation of dioxins from some feedstocks Moderate to high cost, depending on applications Risk of the unsustainable harvesting of feedstocks	(Doan et al 2021, Shakoor et al 2021, Sri Shalini et al 2021, Bolan et al 2023)

(Continued.)

Table 1. (Continued.)

Category	LMT	Description	Emission reduction	CO ₂ removal	Main co-benefits	Main trade-offs	References
Forestry	Afforestation/ Reforestation (AR)	Afforestation: Establishing and growing forests by planting trees in areas where there was no forests before. Reforestation: Replanting and regrowing trees in an area where there was previously forest.	✓	✓	Habitat creation for biodiversity Watershed protection	Land use competition Economic benefits in the mid and long term. Lower resilience to climate change (particularly plantations)	(Humpenöder et al 2014, Krause et al 2017, Lewis et al 2019, Di Sacco et al 2021, Tuinenburg et al 2022)
	Forest management	Management of forests to obtain overall environmental, economic, social and cultural objectives.		✓	Preserves biodiversity, the ecosystem's primary functions and services, and local cultural practices. Higher resilience to climate change. Provides water and nutrient recycling for other land-use types of surroundings.	Economic benefits only in the mid and long term. Lower productivity.	(Torres-Rojo et al 2016, Lindenmayer et al 2012, Aggestam et al 2020)
	Fire management	Combining Indigenous fire management practices with modern prescribed burning techniques to suppress and prevent catastrophic forest fires.	✓		Significant reduction of wildfire risk occurrence and impacts.	Institutional resistance to replacing conventional fire suppression policies. Conflicts with landowners that use fire for large-scale deforestation.	(Collins et al 2013, Bilbao et al 2019, Morgan et al 2020, Prichard et al 2021)

(Continued.)

Table 1. (Continued.)

Category	LMT	Description	Emission reduction	CO ₂ removal	Main co-benefits	Main trade-offs	References
Bioenergy	Bioenergy with carbon capture and storage (BECCS)	Biomass feedstock is utilised for power generation and the resulting carbon dioxide are captured and stored in geological formations.	✓	✓	Fossil-free energy production for industry, power, and transportation sectors. Waste management.	Increased demand for water, fertiliser and additional land requirements for biomass production. Increased cost Additional labour.	(Humpenöder et al 2014, Bonsch et al 2016, Muri 2018, Turner et al 2018)
Biogenic waste management	Anaerobic fermentation of manures (biogas/compost)	Using animal manure and, food and agriculture waste for methane (energy) production and bio-gas slurry (organic fertiliser) as byproduct.	✓	✓	Off-grid household energy. Improved organic matter levels in agricultural soils.	Require starting and maintenance capital.	(Bruun et al 2014, Bahrs and Angenendt 2019, Bekchanov et al 2019, Lohani et al 2021)
Other ecosystems	Peatland management	Protection, partial or full restoration (returning degrading peatland areas to their original state) of peatlands.	✓	✓	Biodiversity increase. Alternative income for farmers. Eutrophication prevention.	Less income. Long return on investment.	(Carlson et al 2015, Lundin et al 2017, Lunt et al 2019, Harrison et al 2020)
Other ecosystems	Pasture management	Management of pasture in a way that optimises the quality and productivity of the pasture for ensuring ample grazing availability for animals, promoting biodiversity and maintaining soil quality.	✓	✓	Enhanced soil health. Improved water quality.	Increased land requirement. Additional monitoring and management cost.	(Henderson et al 2015, Yang et al 2019, Godde et al 2020, Silveira and Kohmann 2020, Elahi et al 2021)

Table 2. Potential of LMTs at the global level.

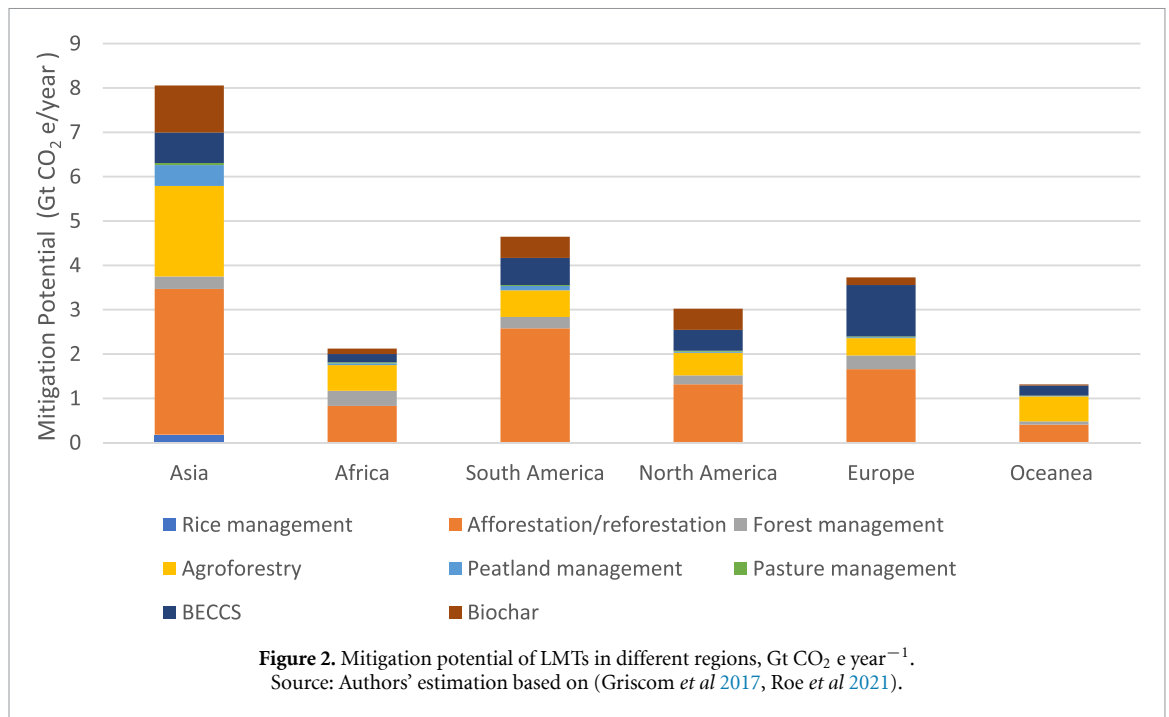
LMT	Technical potential ^a	Economic potential ^b
Agroforestry	0.82–5.6 Gt CO ₂ e year ⁻¹ (Dixon 1995, Roe et al 2021) 0.94–9.4 Gt C (Chapman et al 2020)	8–12 US\$ tCO ₂ e ⁻¹ in Vietnam (Mulia et al 2020), and economically feasible in Europe (Kay et al 2019b) and equal economic viability as monocropping systems (Niether et al 2020)
Rice management	0.21–0.41 Gt CO ₂ e year ⁻¹ (Griscom et al 2017, Ahmed et al 2020a)	Cost saving of around US\$41 tCO ₂ e ⁻¹ (Ahmed et al 2020a)
Reduced tillage	119 MtCO ₂ e year ⁻¹ (Ahmed et al 2020a) 8–12.8 Gt C (Wilkinson 2020)	Negative cost (–260 US\$ tCO ₂ e ⁻¹) (Nayak et al 2015) Net global saving of US\$ 1.5–2.5 trillion (Wilkinson 2020)
Biochar	0.5–6.6 GtCO ₂ e year ⁻¹ (Woolf et al 2010, Smith 2016, Fuss et al 2018)	20–200 US\$ tCO ₂ e ⁻¹ (Fuss et al 2018), cheaper (58–77 US\$ tCO ₂ e ⁻¹) in tropical developing and/or tropical regions (Robb and Joseph 2019)
Afforestation and reforestation	0.5–10.1 GtCO ₂ e year ⁻¹ (FAO 2016, Griscom et al 2017, Austin et al 2020) 205 Gt C (Bastin et al 2019)	Low carbon prices (<\$50 tCO ₂), generally 22–33 \$ tCO ₂ ⁻¹ global, 158–185 US \$ tCO ₂ e ⁻¹ Europe, 0–7 US \$ tCO ₂ e ⁻¹ tropics (Humpenöder et al 2014, Raihan et al 2019) High potential (4.9 GtCO ₂ yr ⁻¹) at higher prices (\$200 tCO ₂ ⁻¹) (Doelman et al 2020)
Forest management	0.4–5.8 GtCO ₂ e year ⁻¹ (FAO 2016, Griscom et al 2017, Sahle et al 2018, Daigneault et al 2022)	60–118 US \$ tCO ₂ e ⁻¹ global, 34–63 US \$ tCO ₂ e ⁻¹ tropics, 198–274 US \$ tCO ₂ e ⁻¹ Europe (Raihan et al 2019; Griscom et al 2017)
Fire management	0.21–1.42 GtCO ₂ e year ⁻¹ (Arora and Melton 2018, Griscom et al 2017)	AUD 11.90 /tCO ₂ ⁻¹ (Lipsett-Moore et al 2018) Significant reduction in managing costs compared to fire-fighting (Russell-Smith et al 2017)
BECCS	0.5–5 GtCO ₂ e year ⁻¹ (Canadell and Schulze 2014, Fuss et al 2018, Roe et al 2019, Ai et al 2021)	Cost ranges from 100 to 200 USD tCO ₂ ⁻¹ (Fuss et al 2018, Humpenöder et al 2014), with the highest cost in South America (70–260 USD tCO ₂ ⁻¹) (Samaniego et al 2021)
Anaerobic digestion of animal manures (Biogas)	0.26–1.26 GtCO ₂ e year ⁻¹ (Jain et al 2019, Ahmed et al 2020a)	\$300 to \$1,000 (Indonesia), depending on the type and scale of the digesters (Schenck 2018). Beneficial around the African countries (small scale) and larger digester in Europe (Hendroko et al 2015, Jabłoński et al 2017, Skovsgaard 2017)
Peatland management	0.8–2.6 GtCO ₂ e year ⁻¹ (Joosten 2009, Griscom et al 2017, Leifeld and Menichetti 2018, Leifeld et al 2019, Strack et al 2022, UNEP 2022b)	\$1225–2,300 ha ⁻¹ Indonesia, UK, Finland, Canada, the Russian/German PeatRus project and Indonesia (Artz et al 2018, Convention on Wetlands 2021)
Pasture management	0.3–1.1 GtCO ₂ e year ⁻¹ (Henderson et al 2015, Griscom et al 2017, Scurlock and Hall 1998)	0.14 Gt CO ₂ yr ⁻¹ at US\$20 t ⁻¹ CO ₂ -e and 0.8 Gt CO ₂ yr ⁻¹ in US\$100 t CO ₂ -e ⁻¹ (Godde et al 2020)

^a highest/lowest estimate of studies assessed. Source: Authors' estimations based on various sources.

^b includes cost of implementation and cost saving.

potential, including integrated soil fertility management (ISFM), organic agriculture and reduced tillage. However, these LMTs have important co-benefits

such as reducing soil erosion, avoiding land degradation and maintaining soil functions. Information on the mitigation potential of several agriculture based



LMTs is limited since they tend to be considered primarily as providing economic and other environmental benefits, rather than contributing to climate change mitigation.

There are significant gaps in the data on and our understanding of the potential contribution of LMTs at different levels. At the continental level, studies on the regional potential of LMTs are scarce. We need more knowledge about which soils have the best potential to mitigate and store additional carbon in the form of soil organic matter and which soil would reduce crop yield through application of LMT (Soane *et al* 2012, Dynarski *et al* 2020). We also need a better understanding of the suitability of, and options related to different agroforestry systems in different regions in order to estimate their mitigation potential.

4. What are the barriers to scaling up LMTs?

Large-scale application of LMTs requires their adoption by a critical mass of stakeholders. However, several factors or barriers can constrain the adoption or scaling up of LMTs, affecting the realisation of their mitigation potential. The barriers to their adoption may not be cost-related. Even at comparatively low costs, barriers—such as access, values and infrastructure—can hinder LMT uptake. The availability of facilitators that foster stakeholder engagement, especially if this involves different knowledge, perceptions and experience, different cultures or different languages, can significantly reduce effective LMT implementation in some contexts (Bilbao *et al* 2019). In this context, we broadly classified the barriers to LMT deployment: (1) socio-cultural; (2) technological; (3) economic; (4) institutional; and (5) ethical.

These are discussed and further sub-categorised in the following sections.

4.1. Socio-cultural barriers

Socio-cultural barriers to LMTs adoption originate mainly from social norms and cultural and ethical values which might result in an unwillingness to adopt a certain technology and a reluctance to deviate from traditions and social practices. Socio-cultural barriers can be grouped into sub-barriers (table 3): (i) norms and values; (ii) knowledge and perception; and (iii) behaviour.

4.1.1. Norms and values

Several studies highlight that socio-cultural barriers arise from social norms and values due to cultural attachment and ingrained belief in the traditional practice, which hugely affects adoption of LMTs. For example, in the case of dry-seeded rice, the new technology requires drilling or broadcasting without tillage or with minimum tillage instead of planting rice seedlings in nurseries and transplanting them after two to three weeks (Gupta *et al* 2011). Farmers are reluctant to abruptly change their traditional way of transplanting rice seedlings into puddled rice fields. Similarly, low input soil 'mining' systems, alternating with fallow periods, is standard practice in many countries in sub-Saharan Africa and integration of organic resources and mineral fertiliser in ISFM adoption represents a deviation from farmers' traditional practices (Vanlauwe and Giller 2006, Mucheru-Muna *et al* 2021). Biogas applications, which include animal and/or human waste as feedstock, can be seen as a cultural barrier and deter adoption by farmers due to the fear of cultural stigma (Bekchanov *et al* 2019, Williams *et al* 2022). Engaging farmers to

Table 3. Socio-cultural sub-barriers to LMT deployment.

Sub-barrier	Description
Norms and values	Traditional belief (DEFRA 2017, Brown <i>et al</i> 2021) Cultural affiliation to a traditional production system (cultural heritage) (Nyong <i>et al</i> 2007, Stoy <i>et al</i> 2018) Cultural norm (Guteta and Abegaz 2016, Sapbamrer and Thammachai 2021)
Knowledge and perception	Lack of knowledge (Tschora and Cherubini 2020, Lohani <i>et al</i> 2021, Mucheru-Muna <i>et al</i> 2021) Limited awareness of the value and benefits of LMT implementation (Gough <i>et al</i> 2018b, Lee and Gambiza 2022) Low social acceptance (Wolske <i>et al</i> 2019, Raimi 2021) Social pressure against LMTs (Bekchanov <i>et al</i> 2019, Williams <i>et al</i> 2022) Perceived threats from LMTs (Willott 2004, Fuss and Johnsson 2021)
Behaviour	Difficulty in the long-term decision for transition (Green and Raygorodetsky 2010, Sapbamrer and Thammachai 2021) Lack of trust (Morgan and Murdoch 2000, Bilbao <i>et al</i> 2019, Fan <i>et al</i> 2022) A habit of relying on conventional practice (Vanlauwe and Giller 2006, Gupta <i>et al</i> 2011, Bilbao <i>et al</i> 2019)

adopt a LMT is sometimes challenging because of the ingrained belief of farmers. For example, in the UK and Switzerland, farmers are less interested in agroforestry practices due to their belief that agriculture and forestry are separate activities (DEFRA 2017).

4.1.2. Knowledge and perception

Lack of knowledge is generally considered as the main barrier to adopting LMTs at the farm level, and it can be due to lack of education and/or lack of communication with agriculture extension agents (Casagrande *et al* 2016). For example, higher educational levels are correlated directly to level of knowledge and, thus, to adoption of organic farming (Karki *et al* 2011) and ISFM (Abukari and Abukari 2020, Mucheru-Muna *et al* 2021). Similarly, frequency of contact with agriculture advisers or experts is essential for filling knowledge gaps (Wollni and Andersson 2014, Sapbamrer and Thammachai 2021). However, increasing the frequency of contact with experts or extension agents may not always contribute to an increase in the adoption of LMTs, since what matters is the quality of the information (Bavorová *et al* 2020). Therefore, the quality of the knowledge transferred to the farmers is crucial for LMTs adoption. Awareness and understanding can be improved through training and other capacity-building to increase adoption of LMTs (Minasny *et al* 2011, Bößner *et al* 2019).

Societies can perceive threats and trade-offs related to (new) technologies and practices and, thus, may oppose certain LMTs, hindering the LMT diffusion process. For example, local communities have opposed peatland restoration projects due to perceived fear of flooding and disease (Willott 2004, Schaafsma *et al* 2017). Similarly, perceived threat of forest fires to biodiversity conservation and natural resource management have hindered the traditional

fire management practices of Indigenous People in protected areas (Bilbao *et al* 2019). Peer pressure to resist use of LMTs occurs influential members of societies do not accept the new practices or if large numbers of society members are against it (Elahi *et al* 2021, Sapbamrer and Thammachai 2021). BECCS, which requires bioenergy crops, has lower social acceptance than biomass from waste used for energy purposes (Fuss and Johnsson 2021). Although, BECCS seems to have greater potential for application in high-income countries, several BECCS projects in many countries have been either put on hold or cancelled due to protests against storage of carbon dioxide in geological formations (Fridahl and Lehtveer 2018), which is perceived as tampering with nature (Raimi 2021). Despite high technical potential, BECCS is not in the horizon of most lower-income economies, as it is considered a very high-cost alternative to other LMTs, and threat to food security due to competition for land. This is in line with the trade-off between land use for climate mitigation and land use for food supply, often summarised under the fuel versus food debate (Rosillo-Calle and Johnson 2010, Babin *et al* 2021).

4.1.3. Behaviour

Farmers' behaviour has been described as a critical barrier to adoption of LMTs. Existing infrastructure, society and governing institutions shape the behaviour of farmers, making change challenging and resulting in a lock-in process (Kjerulf Petersen and Holst Andersen 2009). Farmers generally have a habit of making only short-term decisions, which makes difficult for them to transition to a new LMT practice, such as agroforestry, afforestation or organic farming, which require long-term investment decisions (Soane *et al* 2012, Ollinaho and Kröger 2021, Sapbamrer and

Table 4. Technological sub-barriers to LMT deployment.

Sub-barrier	Description
Complexity	Difficult to adopt due to the complexity of LMTs for farmers/land managers (Casagrande <i>et al</i> 2016, Bilbao <i>et al</i> 2019) Requiring high management skills (Mahajan <i>et al</i> 2009, Soane <i>et al</i> 2012, Lamers <i>et al</i> 2015)
Resources	Difficulty in access to specialised machinery (Casagrande <i>et al</i> 2016, Jat <i>et al</i> 2020, Somasundaram <i>et al</i> 2020) Unavailability of transportation infrastructure (Guteta and Abegaz 2016, Turner <i>et al</i> 2018, Convention on Wetlands 2021) Lack of access to inputs (Ogwu <i>et al</i> 2018, Adolwa <i>et al</i> 2019b, Convention on Wetlands 2021) Limited/no access to credit (Bellwood-Howard 2014, Lohani <i>et al</i> 2021) Limited extension facilities (Thapa and Rattanasuteerakul 2011, Sapbamrer and Thammachai 2021)
Development	Lack of development of efficient monitoring, reporting and verification (Adevale <i>et al</i> 2018, Fuglestedt <i>et al</i> 2018, Strefler <i>et al</i> 2021, UNEP 2022b) Large uncertainties about the benefits of an LMT (Creutzig <i>et al</i> 2021, Donnison <i>et al</i> 2020, Sandalow <i>et al</i> 2021, Yang <i>et al</i> 2021) Limited scientific understanding of land suitability (Baik <i>et al</i> 2018, Babin <i>et al</i> 2021) Technological readiness (Farooq <i>et al</i> 2011, IPCC 2022)

Thammachai 2021). In addition, many farmers do not trust a new technology or believe in its promise until they can see its actual benefits. For example, many farmers did not trust using organic amendments after being encouraged to modernise their synthetic fertiliser techniques (Morgan and Murdoch 2000). Resistance to a LMT often originates from the earlier over-reliance of decision-makers and policy-makers on technology. For example, some forest firefighters and other government institutions in Latin America are reluctant to adopt integrated fire management (IFM) (including Indigenous Peoples' traditional practices). Despite the huge expense and low effectiveness of wildfire combat methods, there is a great prejudice and underestimation of Indigenous people's or local communities' traditional fire management methods which have been used for thousands of years in their territories (Bilbao *et al* 2019).

4.2. Technological barriers

Technological barriers to LMTs are generally associated with inadequate development of the technology and the lack of infrastructure to support its deployment. Technological barriers include technology complexity, resources and stage of development of LMT (table 4).

4.2.1. Complexity

Some LMTs are complex and difficult for farmers to adopt since they require changes in a set of farming practices. However, the traditional extension system focuses only on the LMTs, and ignores implementation, which, to be successful, requires a whole system approach. For example, some LMTs (e.g. paludiculture, reduced tillage, dry-seeded rice) require sophisticated management skills to avoid yield losses (Convention on Wetlands 2021, Tanneberger *et al*

2021a). Accumulation of such skills requires appropriate technical support. Moreover, advanced management practices, including control of eutrophication in restored peatlands (Lamers *et al* 2015), weed management in reduced tillage and dry-seeded rice areas (Mahajan *et al* 2009, Soane *et al* 2012), are required to avoid the negative side effects of these LMTs. The complexity of LMTs has led to high uncertainty about their mitigation potential in no-tillage and reduced tillage national GHG inventories, which makes cost-benefit analyses difficult (Winiwarter and Muik 2010, Schweizerisch Eidgenossenschaft 2020, Tiemeyer *et al* 2020).

4.2.2. Resources

Lack of access to inputs is discussed in the literature as an important barrier to implementation of LMTs. For instance, paludiculture, dry-seeded rice and reduced tillage systems require new types of farming equipment which might be difficult to access by resource-poor farmers. For example, difficulties involved in accessing specialised machinery (e.g. tractor-drawn seed-cum-fertiliser drilling equipment) by small farmers has restricted adoption of reduced tillage systems (Casagrande *et al* 2016, Somasundaram *et al* 2020). Although farmers might be keen to adopt these new practices, unavailability of inputs, such as new plant species and transportation infrastructure, is restricting adoption of paludiculture (Convention on Wetlands 2021) and ISFM (Guteta and Abegaz 2016) respectively. For some LMTs, technology is either unavailable or very few management options are available to make LMTs an attractive choice due to different challenges such as limited pest pressure management options in organic agriculture, lack of suitable varieties for dry-seeded rice and, difficulty of weed management in reduced tillage, dry-seeded rice

and organic agriculture (Farooq *et al* 2011, Matloob *et al* 2015, Wang *et al* 2017, Muneret *et al* 2018).

Technological barriers were observed related to a need for knowledge about how different LMTs should be applied, stemming from a lack of access to extension facilities. Lower-income countries lack appropriate dissemination systems and extension facilities related to organic agriculture, dry-seeded rice and ISFM. In developing countries, there are too few trained personnel and a lack of technical support for farmers, could be seen as a need for capacity building (Dhyani *et al* 2021, Lee and Gambiza 2022). Similar observations have been made by Tschora and Cherubini (2020) for West Africa, where adoption of a LMT can be risky for farmers due to limited knowledge and difficulty in accessing capital. Access to capital investment is equally important for inputs other than mineral fertiliser; currently, credit is often available only to purchase chemical fertilisers (Bellwood-Howard 2014, Sapbamrer and Thammachai 2021).

4.2.3. Development

Insufficient technological development limits LMT deployment. Existing rice varieties that currently are grown from transplanted seedlings, are not as successful when used for dry-seeded cultivation as they do not grow well in reduced oxygen microenvironment during the early stages (Farooq *et al* 2011). Therefore, dry-seeded rice methods require three or four times the amount of seeds compared to conventional transplanting practices, and this increases the farmers' production costs. The wide range of estimates for carbon sequestration and emissions reduction potential for many LMTs constrain market developments, since it is difficult to quantify the return from investments. For example, the effectiveness and impact of biochar applications depend significantly on the choice of feedstock, the pyrolysis protocol and the soil characteristics (Smith 2016, Smith *et al* 2019b). This makes it difficult to standardise or optimise biochar applications, even under similar agricultural or climate conditions, and is confusing for stakeholders (Yang *et al* 2021). These types of issues to an extent, apply also to BECCS, in terms of significant variation in the impacts on productivity and land use of different bioenergy crops and uncertainties related to transporting and storing carbon dioxide and the related infrastructure (Sandalow *et al* 2021). So far, BECCS is limited to the demonstration phase (technology readiness level 6) (IPCC 2022). The technology is possible theoretically but requires further development to achieve large-scale deployment.

Insufficient scientific understanding about which species to focus on to kick-start peatland regeneration for paludiculture is another barrier (Convention on Wetlands 2021). We still have limited knowledge about which soils have the greatest emissions

reduction potential (Soane *et al* 2012) and, especially, which soils will result in reduced yields in no-tillage systems (Lahmar 2010). Absence of streamlined monitoring, reporting and verification protocols has a negative effect on uptake of LMTs at the national level (Dhyani *et al* 2021, Mackey *et al* 2022, Perosa *et al* 2023). Lack of knowledge about LMT implementation is a barrier to better fire management systems. The interpretation of satellite imagery and other fire monitoring techniques by remote sensing can lead to misconceptions in distinguishing between wildfires from prescribed fire uses by local communities if it is not done in cooperation with field technicians or fire-fighting and protection agencies that have adequate knowledge of IFM implemented as LMT. For effective forest fire management, we need a better understanding of the specific fire regimes in different countries, which requires further scientific development (Bilbao *et al* 2019).

4.3. Economic barriers

One of the most important concerns for policy in the context of LMTs is whether the scaling up of these technologies and practices will be economically feasible. Roe *et al* (2021) consider that only 42% of the entire technical global potential of LMTs is economically feasible. Although many LMTs have the greater technical potential to reduce emissions and/or sequester carbon, economic barriers are constraining their diffusion. The main economic barriers are insufficient initial investment capital, economic losses from LMTs and, unavailability of incentive and subsidy schemes. These barriers can be categorised as cost, income and value related sub-barriers (table 5).

4.3.1. Costs

The high costs related to implementation of LMTs constrain their adoption and diffusion, since they require farmers and forest users to have sufficient capital to cover the significant initial costs of transitioning to LMTs. Adopting LMTs often incurs additional costs than conventional practices (agroforestry, biogas, AR) (Lohani *et al* 2021, Meyer *et al* 2021). There are also additional costs related to pest and weed control (dry seeded rice, reduced tillage) (Mahajan *et al* 2009, Soane *et al* 2012), fertilisers and improved seeds (ISFM) (Bryan *et al* 2013a, Bellwood-Howard 2014) and specialised machinery (paludiculture, dry seeded rice, reduced tillage, biochar) (Flammini *et al* 2020, Tanneberger *et al* 2021b). Small farmers will be reluctant to adopt LMT if this requires expensive technical support or machinery. For example, in the case of pasture management in Europe, farmers need technical support and mentoring (Wilson and Hart 2000). However, this type of support is expensive and, unless it involves external finance, will not necessarily provide a financial return. The higher cost of inputs and organic certification is reported as an important

Table 5. Economic sub-barriers to LMT deployment.

Sub-barrier	Description
Cost	Unable to afford expensive specialised machinery (Casagrande <i>et al</i> 2016, Flammini <i>et al</i> 2020, Jat <i>et al</i> 2020, Tanneberger <i>et al</i> 2021b) Large initial investment (Do <i>et al</i> 2020, Flammini <i>et al</i> 2020) Expensive to deploy at a scale where there is large potential (Smith 2016, Lohani <i>et al</i> 2021)
Income	Possibility of reduced income due to trade-offs (DEFRA 2017, Böttcher <i>et al</i> 2021, Sapbamrer and Thammachai 2021) Transitional period with higher production costs and lower income (Meng <i>et al</i> 2017, Soane <i>et al</i> 2012, Do <i>et al</i> 2020) Lack of incentives (Harper <i>et al</i> 2017, Wichmann 2017, Serrano <i>et al</i> 2020)
Value	Difficult to give value to the non-monetary benefits (ecosystem services) of LMTs (Donnison <i>et al</i> 2020, Kay <i>et al</i> 2019a)

constraint to adoption of organic farming (Jouzi *et al* 2017, Sapbamrer and Thammachai 2021). Similarly, the high initial and maintenance costs related to agroforestry are important barriers and, in the first few years, can generate net losses until tree products, such as fruit and timber, can be harvested (Do *et al* 2020).

LMTs such as BECCS incur high upfront implementation costs due to the need for developing comprehensive system for biomass production, energy production and carbon storage sites. Cost may further increase if these processes are separately across different countries. BECCS is relatively expensive compared to other land-based solutions and is not currently appropriate for lower-income countries (Samaniego *et al* 2021). Biochar also has high upfront implementation costs in places where pyrolysis systems are not well established. In low-income countries, introducing a large-scale biochar production with low cost and efficient biochar technology is a major challenge (Cornelissen *et al* 2016). A lower-cost alternative would be artisanal biochar that might be made on-farm with small-scale simple pyrolysis units. However, the quality of artisanal biochar will vary, with different effects on soil fertility and crop yields. Large-scale biochar implementation to produce biochar of standardised quality is more expensive and, thus, would be less popular in lower-income and emerging countries, where the high cost of establishing and maintaining large-scale pyrolysis units makes them infeasible (Flammini *et al* 2020). Therefore, in lower-income countries including Sub Saharan Africa, it is important either make revenue guarantee or support for initial purchase cost of biochar as soil amendment to ensure demand (Dickinson *et al* 2015). In many lower-income countries of Asia and Africa, the case of biogenic waste management and organic fertilisers, the high investment costs related to installing biogas digesters can exceed the average farming household's income (Lohani *et al* 2021). LMTs should be affordable with manageable investment costs to allow most households to adopt these systems.

4.3.2. Income

Reduced income is another deterrent to farmers' adoption of LMTs. At the individual level, the economic prospects of individual farmers matter and high investment cost and long transition period associated with reduced income, which makes the transition to implementing LMT more challenging (Sapbamrer and Thammachai 2021). Studies suggests that farmers generally expect to receive a reduced income from agroforestry, due to greater weed and pest infestations, and difficulty in accessing crops with farm machinery (DEFRA 2017, Graves *et al* 2017). However, this is not necessarily the case; meta-analysis shows that agroforestry effectively reduces weed, pest and disease pressures in perennial crops (e.g. coffee, plantain, cocoa) (Pumariño *et al* 2015). Forest management practices can also result in reduced income due to lower yields, severely affecting interest in private forests (Böttcher *et al* 2021). Also, in the first few years of adopting reduced tillage systems and organic farming, yields are likely to be smaller (Seufert *et al* 2012, Soane *et al* 2012, Meng *et al* 2017). Reduced income due to yield losses can be significant and occur if the farmer lacks good LMT implementation skills. For example, in the case of dry-seeded rice, reduced tillage and organic farming systems, a lack of knowledge about appropriate weed management results in lower yields and reduced income (Soane *et al* 2012, Ahmed *et al* 2015, Meng *et al* 2017).

4.3.3. Value

The lack of valorizing co-benefits of LMTs is another barrier to their implementation. LMTs have received global attention because of their potential value for mitigating climate change, enhancing ecosystem productivity and resilience, and supporting biodiversity. For example, biochar has several co-benefits in terms of overall productivity and soil conditioning, including increased microbial activity, nutrient cycling, soil respiration, denitrification, increased availability of certain elements and reduced acidity

(Sánchez-Monedero *et al* 2019). The system-wide benefits of agroforestry include improved product diversification (fruits, timber, firewood, livestock feed, construction material, medicinal), microclimate modifications and improved soil health (Jose 2009, Nair *et al* 2021).

Carbon sequestration as the result of implementation of LMTs is still considered an indirect co-benefit by many end-users. It is not the main focus of land management practices and there is a lack of proper farmer incentive systems related to carbon removal. Similarly, elsewhere in the world, policies do not focus on co-benefits, such as biodiversity, soil fertility enhancement, decreased soil erosion and nutrient losses. In Indonesia and other South East Asian countries, national governments are focused mainly on land management practices to achieve food security and it is difficult to convince them to consider LMTs in their mitigation planning decisions (Sardiana 2021). For example, in Thailand, the economic aspects of different crops (e.g. there is more demand for rice compared to coconuts) matter more than carbon capture based on land use (Gnanavelrajah *et al* 2008). Unless account is taken of the various co-benefits and appropriately incentivised, it will be difficult to attract investment in LMTs to support carbon sequestration schemes.

4.4. Institutional barriers

The main institutional barriers are the need for clear and favourable policies and regulations. The institutional barriers to scaling up of LMTs can be categorised as policy, governance and regulation issues (table 6).

4.4.1. Policy

Despite growing recognition of the potential of LMTs to mitigate climate change and provide other economic and non-economic co-benefits, many countries lack an enabling and supportive policy framework for their large-scale deployment. In the EU context, lack of a comprehensive enabling and supporting policy framework means that there is still a low level of demand for biochar, which is an institutional barrier to the widespread diffusion of the biochar system (Verde and Chiaramonti 2021). Wichmann (2017) points to an absence of agricultural policies setting explicit incentives for large-scale implementation of paludiculture in Europe. Also, lack of policies offering financial incentives to reduce GHGs, has been identified as a market failure for LMTs such as ISFM (Bryan *et al* 2013a). Appropriate policy support for small farmers' adoption of LMT is generally lacking in lower-income countries. For example, lack of support to provide affordable access to machinery (e.g. dry-seeded rice) or credit (ISFM) (Farooq *et al* 2011, Bellwood-Howard 2014), has hindered the adoption of LMT by poorer farmers.

Most countries still lack national agroforestry policies and guidelines. Although some countries, for example, Nepal, do have national policies in place, their implementation at all sub-national levels has yet to be realised. In developing countries, tedious administrative processes for the use of community forests hinder the access to the benefits of the newly obtained rights by the local communities (Hajjar *et al* 2021). These include introduction of regulation that recentralises forest management to the government offices through the mandatory administrative burden for registration, validation and verification procedures for harvest and sale of forest products, mainly timber (Pulhin and Dressler 2009, Aryal *et al* 2020). Similarly, policy support and financial incentives for reducing GHGs using LMTs are either lacking, insufficient or unclear. The lack of policy coherence is a significant barrier to LMT deployment which does not consider land-based mitigation when formulating and implementing national land use policies (Regina *et al* 2016).

Lack of policy support is attributable to several factors, including high levels of uncertainty in national GHG inventories, the pricing of sequestered carbon (Rypdal and Winiwarter 2001, Laganière *et al* 2017, Maillard *et al* 2017, Torvanger 2019, Dhyani *et al* 2021, Mackey *et al* 2022) and the difficulties involved in assessing additionality and permanence (Paul *et al* 2023). In the case of large-scale deployment of BECCS, support for technological development will be needed (Gough *et al* 2018a, Zetterberg *et al* 2021). In the biochar case, difficulties related to applying universal technical standards across different countries and regions is hindering uptake, since production methods and biomass sources and their effects differ widely (Joseph *et al* 2021, Kurniawan *et al* 2023). Lack of policy support for the long-term investment is reducing the willingness of farmers and land managers to invest in many LMTs such as agroforestry (Neef and Heidhues 1994, Gosling *et al* 2020), organic farming (Lotter 2015, Jouzi *et al* 2017), forest management and AR (MacDicken *et al* 2015, Harper *et al* 2017, Oldekop *et al* 2019).

4.4.2. Regulation

Regulatory support can make conventional technology and practices appear cheaper and more effective than LMT. In Germany, use of glyphosate herbicides is prohibited from 2024 (BMU 2019), which could affect weed management in reduced tillage practices and, in turn, affect yields. Similarly, public policies and legislation on fire suppression and prevention have prevented implementation of IFM in forests (Bilbao *et al* 2019). In many countries, fire use in forests is considered a criminal activity, despite its proven effects in terms of minimising major uncontrolled forest fires (Myers 2007). Similarly, many countries have insecure land and/or tree tenure for Indigenous People (Borelli *et al* 2019),

Table 6. Institutional sub-barriers to LMT deployment.

Sub-barrier	Description
Policy	Lack of policy support mechanism to set explicit incentives (Bryan <i>et al</i> 2013b, Mosquera-Losada <i>et al</i> 2018, Verde and Chiaramonti 2021) Lack of policy implementation (Kanowski <i>et al</i> 2011, Kalaba 2016, Gough <i>et al</i> 2018a, Aryal <i>et al</i> 2020) Disinterest of policymakers (Haupt and Lupke 2007, Kalaba 2016, Harper <i>et al</i> 2017)
Governance	Lack of cross-sectoral responsibility-sharing (Korhonen-Kurki <i>et al</i> 2016, Rosa <i>et al</i> 2021) Top-down approach (Ravikumar <i>et al</i> 2018, Kusnandar <i>et al</i> 2019) Coordination between stakeholders (Jew <i>et al</i> 2020, Baig <i>et al</i> 2021) Lack of proper monitoring (Borelli <i>et al</i> 2019 UNEP 2022b)
Regulation	Counter-productive public policies and legislation (Myers 2007, Bilbao <i>et al</i> 2019, BMU 2019) Lack of standards and protocols to measure carbon sequestration (Torvanger 2019, Paul <i>et al</i> 2023)

which limits the adoption of LMTs that require long-term investment, such as agroforestry, forest management and AR. Lack of political interest and related scepticism has, to a certain degree, impaired the policy process and the potential of forestry clean development mechanisms (Haupt and Von Lupke 2007). Lack of uniform standards and protocols to measure carbon sequestration has been a major barrier to the promotion of LMTs (Torvanger 2019, Paul *et al* 2023).

4.4.3. Governance

Poor governance is a major barrier to the adoption and diffusion of LMTs. Implementing LMTs at the national level needs proper planning and coordination across multiple sectors including agriculture, forestry, environment, industry, infrastructure, land and housing. These sectors are intertwined with land use changes, which involve shared responsibilities, but also can compete. Without multi-level and multi-sectoral governance, there is a high likelihood of negative consequences resulting from the land-use-based interventions. For example, it has been shown that, instead of targeted sustainable forest management, deforestation or forest degradation have occurred due to lack of proper coordination among multiple sectors and the sharing of responsibilities across sectors (Kalaba 2016, Ravikumar *et al* 2018). Other studies show that lack of proper coordination among stakeholders has limited adoption of reduced tillage systems (Jew *et al* 2020) and agroforestry (Baig *et al* 2021). Borelli *et al* (2019) warned that ignoring the governance structure can reduce the effectiveness of implementing an agroforestry policy. Although there are institutional mechanisms to govern LMTs implementation, a top-down approach can hinder implementation of LMTs since the interventions do not match the needs of locals (Ravikumar *et al* 2018, Kusnandar *et al* 2019), and may even place the livelihoods of local communities at risk. Similarly, a few studies highlight insufficient monitoring as hindering the effectiveness of agroforestry implementation (Borelli *et al* 2019). Uncertainty in transforming

traditional governance structures and policy-making has been seen as one of the main barriers to future implementation of BECCS (Torvanger 2019, Hanssen *et al* 2020, Sandalow *et al* 2021).

4.5. Ethical barriers

Ethical barriers are associated, mainly, to large-scale land use changes to reduce emissions and sequester carbon. Ethical barriers can be categorised as conflicts, trade-offs and fairness (table 7). Ethical concerns are more prominent in some LMTs, including BECCS, AR, and forest management, which could be increasingly deployed in Asia, Africa and Latin America, where integrated assessment models (IAMs) have demonstrated their high potential due to their wide applicability and the high potential for scaling up (Roe *et al* 2021). These are the regions that, historically, have contributed the least to climate change.

4.5.1. Conflict

Conflicts related to forestry LMT arise as a result of the vested interests of diverse stakeholders in the utilization and management of forest resources (Nousiainen and Mola-Yudego 2022). Policy makers might prioritise forest protection and carbon removal, while farmers and forest users may be more interested in the direct economic benefits. Equitable sharing of the benefits can be difficult, especially in managing common resources such as community forests. Social or cultural conflicts tend to be more prevalent in countries with no or poorly defined land rights, and accumulation of large proportion of land in a limited upper class elites (Larson *et al* 2013, Gutiérrez-Zamora and Estrada 2020). For instance, rapid proliferation and expansion of programmes and activities to protect against forest fires in the Amazonian countries, implemented by government and non-governmental organisations, lack coordination, guidelines and formal authorisations and have led to conflicts between institutions (Mistry *et al* 2016, Bilbao *et al* 2019). Social and land-use conflicts in several regions have contributed to displacing Indigenous populations and rural

Table 7. Ethical sub barriers to LMT deployment.

Sub-barrier	Description
Conflicts	Risks of land grabbing (Carter <i>et al</i> 2017, Scheidel and Work 2018, Xu 2018, Hansson <i>et al</i> 2020) Issue of equitable benefit sharing (Khatun <i>et al</i> 2015, Essougong <i>et al</i> 2019) Issue of social conflicts (Hoang <i>et al</i> 2019, Santika <i>et al</i> 2019, Gutiérrez-Zamora and Hernández Estrada 2020)
Trade-offs	Land availability and competition with other land uses (Rosillo-Calle and Johnson 2010, Humpenöder <i>et al</i> 2014, Griscom <i>et al</i> 2017) Possible increase in food prices and compromise food security (Fuss <i>et al</i> 2018, Fujimori <i>et al</i> 2022, Gong <i>et al</i> 2022, Vera <i>et al</i> 2022) Negative effect on the environment (Kumar and Ladha 2011, Bonsch <i>et al</i> 2016, Williamson 2016, Babin <i>et al</i> 2021)
Fairness	Limited access of women and minority groups to resources and land (Astuti and McGregor 2017, Borelli <i>et al</i> 2019) No consideration of the rights of Indigenous People and local communities (Bilbao <i>et al</i> 2019, Walker <i>et al</i> 2020)

communities from their traditional territories, pushing them into poverty, marginalisation and illegal activities. Unawareness of these realities can affect the effective implementation of LMTs through multilateral or bilateral international cooperation initiatives, as in the case of the REDD+ program in the Latin American countries (Armenteras *et al* 2015, Walcott *et al* 2015).

4.5.2. Fairness

The lack of fairness stemming from historically constructed power relations and patterns of disadvantage and advantage are deeply entrenched in social, political, and economic realities since colonial times representing a constraining factor for the design and also deployment of LMTs on a large scale. Policymakers often assume that mainstream science and economy are better suited for environmental and social decisions, including LMTs design, compared with indigenous governance and knowledge (Howitt *et al* 2013, Bilbao *et al* 2019). This thinking continues to dominate despite evidence of sustainable practices by Indigenous Peoples and local communities for conserving biodiversity, reducing deforestation and climate mitigation (Walker *et al* 2020). Management structures, procedures and plans are usually developed without the participation of Indigenous Peoples and local communities in many countries globally. In addition, they restrict and reshape Indigenous Peoples' access to, control over and benefits from their traditional territories and resources. Although many countries have formulated laws on Indigenous Peoples' rights, land and tree tenure insecurity remain contentious due to the lack of or weak supervision, which increases local elites' control over land and resources (Borelli *et al* 2019). As a result, numerous land disputes remain unsolved and increase uncertainty about land restitution and relevant jurisdictions for developing

infrastructure projects (Bains 2015, Muthama *et al* 2019, Pasternak 2022).

LMT implementation could also perpetuate and deepen historical inequalities through changes to land use changes. For example, 'zero' forest fire management programmes implemented by Brazilian and other Amazonian countries' governmental agencies and non-governmental organisations have reduced control over the management of Indigenous land, by official indigenous agencies (Falleiro *et al* 2021). Similarly, afforestation or tree planting on grasslands and other land not previously forest, can increase the vulnerability of Indigenous People and reduce their rights if implemented without taking account of Indigenous rights to traditional pastoral livelihoods (Ramprasad *et al* 2020). Similarly, promoting tree-planting can lead to land grabbing at different scales (Carter *et al* 2017, Scheidel and Work 2018, Xu 2018). The significant cross-cultural deficit in key agencies responsible for designing and implementing LMTs drastically limits the achievement of effective, fair and sustainable outcomes for both local stakeholders and the mitigation potential of LMTs.

4.5.3. Trade-offs

LMTs deployment can lead to trade-offs with the environment and social benefits. For example, improved rice management practices which involves soil drying in dry-seeded rice can substantially reduce methane emissions, but increase nitrous oxide emissions (Kumar and Ladha 2011). Trade-offs between crop yields and biodiversity in conventional and organic farming show that organic farming increases biodiversity by almost a quarter (23%), but reduces yields (Gong *et al* 2022). Conflict with goals to preserve biodiversity arise if forest policies and programmes prioritise trees with high carbon sequestration potential and timber values, but low biodiversity values (Caparrós and Jacquemont 2003). At the same

time, the agriculture sector is affected negatively, in terms of food security, due to reduced areas available for crops and decrease in water availability (Vera *et al* 2022). For example, the UK government's net zero plan in land use to increase carbon sequestration and biodiversity can reduce around a fifth of the total cropped area by 2050 (CCC 2020), affecting food security. Large scale deployment of AR can occur only at the expense of reduce pasture area or cropland (Griscom *et al* 2017). Also, large-scale expansion of LMTs could lead to competition with food production due to rivalry over land, water and nutrients (Rosillo-Calle and Johnson 2010, Fuss *et al* 2018, Vera *et al* 2022).

Although fire suppression policies implemented for forest conservation and carbon storage can eventually reduce the area burned (and GHG emission), under more frequent and extreme fire weather conditions (IPCC 2021), these policies are inefficient given their great technical complexity, high risks for fire combatants and high costs, especially for countries with limited resources and extended territory. Additionally, the sustained fuel accumulation in areas under long-term fire exclusion policies and limitations imposed on Indigenous and traditional fire management contribute to more severe fires and, under extreme conditions, 'megafires' (cases in the Amazonia in 2010/2015/2016/2019/2020 and Pantanal 2020) (Bilbao *et al* 2010, Aragão *et al* 2020, UNEP 2022a).

Table 8 summarises the main barriers to implementation of the LMT discussed and how the barriers might be overcome. It should be noted that implementation of two or more LMTs could introduce additional barriers. We encourage further research into the interactions among LMTs, to identify the barriers and risks related to implementing LMT portfolios as well as individual LMTs (see section 5).

5. Discussion

This study was aimed at providing a better understanding of the potential of and barriers to the upscaling of LMTs and informing policy decision-making about land use, to address societal challenges. In this section, we synthesise the findings from the different studies reviewed in sections 3 and 4.

5.1. Mitigation potential

Much studies on LMTs focuses on projections for a single LMT. While many LMTs are not mutually exclusive, they can compete for land and biomass resources. For example, biochar and BECCS compete for the same biomass. Similarly, an increase in afforestation results reduction in areas of cropland and permanent pastures. Therefore, the studies of individual LMTs can lead to large uncertainties regarding the potentials of upscaling LMT implementation,

if these interactions are omitted. At the global level, IAMs (e.g. (Humpeöder *et al* 2014, Roe *et al* 2021)) are often used to study portfolios of LMTs at the local, national and continental levels. They can potentially provide more realistic estimations because they take account of possible overlaps, competition and trade-offs among LMTs and other land use types such as food production (Kreidenweis *et al* 2016). However, one of the drawbacks of existing scenarios used in IAMs is that they rely heavily on solutions such as BECCS and afforestation, since these are more compatible with the essential characteristics of these models and exclude other LMTs (Fuhrman *et al* 2019). Moreover, these kinds of models are often too broad in their spatial resolution to consider the regional differences in the impact of climate change on LMTs, co-benefits, trade-offs, saturation, and reversibility to understand the impact of LMTs on economy and environment (See also Roe *et al* 2021).

The mitigation potential of LMTs is site-specific and heterogeneous—varying by local environment, regions and countries even within the same cropping system or similar forest type. In general, model characteristics, datasets, scenario assumptions and availability of suitable land all affect the mitigation potential of LMTs. Among the selected LMTs, AR and forest management have the highest low cost-high-mitigation potential across continents. AR estimates are subject to significant uncertainty due to varying assumptions related to suitability of new forest area, site specific tree species, costs and achievable rates of carbon sequestration. There is some doubt over whether large-scale afforestation is feasible in the areas with the highest carbon sequestration potential such as the tropics. A large share of afforestation is forecasted to be located in low and middle income regions, particularly in Asia, Latin America and Africa (figure 2), which have high investment risks, poor governance and suffer continued deforestation (Doelman *et al* 2020).

At the global scale, future projections of biomass based LMTs—BECCS and biochar—show high mitigation potential and, thus, are considered a major proportion of the LMT portfolio. BECCS has the potential to achieve reductions of 0.5–5 GtCO₂ e year⁻¹ (Canadell and Schulze 2014, Fuss *et al* 2018, IPCC 2022) and biochar mitigation is estimated to be between 1.8–6.6 GtCO₂ e year⁻¹, depending on the level of sustainable biomass sources (Woolf *et al* 2010). BECCS has a higher potential for large-scale deployment in high-income countries for technology availability, high affordability and low-cost biomass supply chain reasons. BECCS is currently in the demonstration phase; its widespread adoption will require it to be a reliable and cost-effective option compared to other LMTs (van Alphen *et al* 2009, Nemet *et al* 2018). Proper accounting of suitable land for bioenergy, carbon dioxide transportation and underground carbon dioxide storage facilities,

Table 8. Main barriers to LMT deployment and suggestions to overcome them.

LMT	Main barriers	Suggestions	References
Agroforestry	Deprivation of land and tree rights. Need for long-term investment. Perception of reduced income.	Regulation for land and tree rights. Ensure technical and financial support. Awareness and knowledge.	(Borelli <i>et al</i> 2019, Tschora and Cherubini 2020, Dhyani <i>et al</i> 2021)
Dry seeded rice	Difficult to change a set of traditional practices. Lack of access to expensive machinery. Fear of reduced income due to higher weeds.	Awareness and knowledge. Increase access to capital through subsidies or grants. Technical support.	(Kumar and Ladha 2011, Weerakoon <i>et al</i> 2011, Mahajan <i>et al</i> 2013, Mahajan and Chauhan 2015)
Reduced tillage	Reduced income due to higher weeds. Lack of access to expensive machinery.	Technical support. Appropriate incentives via subsidies, loans or grants for machinery.	(Lahmar 2010, Soane <i>et al</i> 2012, Jat <i>et al</i> 2020)
Integrated soil fertility management (ISFM)	Lack of favourable policy. Lack of appropriate infrastructure.	Credit support. Market development.	(Bryan <i>et al</i> 2013a, Bellwood-Howard 2014, Adolwa <i>et al</i> 2019b)
Organic agriculture	Lack of access to credit and initial cost. Limited market due to dependency on higher price premiums.	Financial support, even after transition period. Market development.	(Crowder and Reganold 2015, Sapbamrer and Thammachai 2021)
Biochar	Lack of understanding of indirect benefits. Increased or uncertain costs. Lack of policy support. Difficulty in applying the same standards in different regions due to the variation in production methods and feedstocks.	Knowledge platforms and training. Cross-sectoral coordination lowers the cost. Targeted incentives for farmers. Biochar certification and standardisation schemes. Technical support schemes for pyrolysis systems.	(Lakitan <i>et al</i> 2018, Doan <i>et al</i> 2021, Joseph <i>et al</i> 2021, Verde and Chiaramonti 2021, Yang <i>et al</i> 2021)
Afforestation/ reforestation	Need of long-term investment and no income in the first few years. Chances of monoculture and loss of biodiversity if focused on intensive wood production. Reduction in farmland or pasture.	Grant or subsidy scheme support system. Policy to avoid biodiversity loss. Regulation to avoid the increase in food insecurity.	(Griscom <i>et al</i> 2017, Austin <i>et al</i> 2020, Doelman <i>et al</i> 2020, Mohan <i>et al</i> 2021)
Forest management	Need for long-term investment. Less income due to low wood harvest.	Continued grant or subsidy scheme support system.	(Torres <i>et al</i> 2010, Austin <i>et al</i> 2020, Böttcher <i>et al</i> 2021, Carrilho <i>et al</i> 2022)
Bioenergy with carbon capture and storage (BECCS)	Lower level of technology readiness. Higher costs mainly in low-income countries. Low social acceptability due to the reduction in food crops' availability.	Foster technology development and commercialisation. Develop low-cost supply chains even for low-income countries. Awareness and policy to ensure increased acceptance.	(Baik <i>et al</i> 2018, Fridahl and Lehtveer 2018, Muri 2018, Wolske <i>et al</i> 2019, Donnison <i>et al</i> 2020, Fuss and Johnsson 2021, Rosa <i>et al</i> 2021, McElwee 2023)
Anaerobic fermentation of manures (biogas/-compost)	Low cultural acceptability as dung or human waste is used. High investment cost.	Increase awareness and knowledge. Provide financial incentives. Develop affordable installation technology.	(Bößner <i>et al</i> 2019, Lohani <i>et al</i> 2021, Williams <i>et al</i> 2022)

(Continued.)

Table 8. (Continued.)

LMT	Main barriers	Suggestions	References
Pasture management	Lack of knowledge of complex pasture management systems.	Technical support.	(Ghajar and Tracy 2021, Horn and Isselstein 2022)
Peatland management	Lack of access to expensive machinery. Low technological knowledge.	Increase access to capital through subsidies or grants. Technical support.	(Joosten and Duene 2021, Tanneberger <i>et al</i> 2021b, UNEP 2022b)
Fire management	Counter-productive zero forest fire policies. Need for complex forest fire detection and monitoring systems and lack of coordination between agencies.	Regulation to support the combination of traditional and modern forest fire management. Increased access to resources and developed governance framework.	(Bilbao <i>et al</i> 2019, Falleiro <i>et al</i> 2021)

disaggregated by region, is needed to plan large-scale BECCS deployment. Biochar can be deployed sooner and at a lower price (Woolf *et al* 2016) in both low and high-income countries. However, it tends to have greater co-benefits in low-latitude and/or low-income countries due to its value for agricultural productivity.

The potential for large-scale deployment of BECCS and biochar is much lower in low-income countries, in the short term, at least, due to a lack of financial resources, unavailability of technology, higher implementation costs and variations in performance (especially in the case of biochar). However, it is likely that these LMTs will be the first to achieve full-scale deployment in high-income countries, but this will require large-scale production and transportation of biomass from low-income countries. Without good governance systems, continuous large-scale biomass exports to developed countries will lead to rapid deforestation and monocultures, in addition to reduced cropland areas which will increase food prices and reduce water availability in lower-income countries. Despite their considerable potential, lack of appropriate regulations, mainly in the low-income countries, could lead to ethical issues such as land grabbing and conflicts, displacing the vulnerable communities. In the absence of robust institutional mechanism to deploy LMTs, a commercial plantation can be considered AR, which could contribute to loss of forest, biodiversity, and negatively impact the livelihoods of local communities.

Another issue requiring resolution is the long-term carbon storage by LMTs or the 'soil or biomass carbon lifespan', 'level of permanence' or 'long term security of sequestered carbon'. Carbon storage via BECCS and biochar is potentially secure for over a hundred years and can be considered a carbon pool with a high level of permanence. However, most LMT effects are reversible quickly. Carbon stock gains due to LMT practices, including organic farming, ISFM and reduced tillage, are associated with

lower permanence due to physical losses or microbial decomposition, if the practice is discontinued. Similarly, forest biomass carbon stocks are depleted by deforestation or wildfires. More detailed studies of carbon sequestration related to different LMTs are needed, which would respond to the many calls for a better understanding of the risks to the permanence of sequestered carbon (Gren and Aklilu 2016, Bossio *et al* 2020, Dynarski *et al* 2020, Pan *et al* 2022). Finding ways to deal with different permanence linked to different LMTs, is a major policy concern in the context of the growing number of policies and programmes offering incentives to farmers for sequestering carbon.

Nevertheless, carbon sequestration provides a quantifiable climate benefit even if the landowner reverts to conventional practices (Sierra *et al* 2021). Future studies on the permanence and reversibility of LMT would help policymakers to plan short and long-term investment in LMTs. However, too much focus on LMTs with higher permanence could result in LMTs with high non-economic and wider environmental and social potential, such as improved biodiversity and food security, being overlooked.

5.2. Barriers and injustices

While knowledge and awareness of LMTs and their multiple benefits are increasing, issues related to surmounting the different barriers at multiple scales and creating an enabling environment for scaling up LMTs persist. Efforts for large-scale deployment could trigger questions about the socio-environmental injustices suffered by already vulnerable people, communities and poor regions and countries. Here, we consider the concept of land-based mitigation injustice as an 'increase in inequalities within communities and exacerbating their vulnerabilities as a result of LMT implementation, which involves land-based actions for removal of carbon from the atmosphere or reduction of GHG emissions'. Thus, LMT interventions should focus on prioritising

protection of rights of the marginalised people and indigenous communities, as well as enhancement of their livelihoods while simultaneously achieving multiple benefits from land use, such as climate change mitigation and various ecosystem services.

During large scale deployment of LMTs, it is imperative that the negative consequences for people's livelihoods and marginalised communities, including smallholder farmers and Indigenous People, be avoided entirely. Large-scale deployment of some LMTs will require additional land that could be used to produce food, fibre or other forest products. For example, global scale deployment of afforestation would require large amounts of land, up to 1100 Mha (Doelman *et al* 2020), while BECCS will need a biomass production area of up to 910 Mha (Ai *et al* 2021). Such global land use changes could lead to shrinkage of agricultural land and grassland. Therefore, upscaling LMTs could have negative consequences in the form of competition with other land uses, such as nature conservation and crop production, potentially threatening biodiversity, environment and livelihoods (Creutzig *et al* 2021). Hence, the basic principles underlying any scaling up of LMTs should minimise the negative consequences for socio-cultural, environmental and economic goals while increasing carbon sequestration and reducing emissions. A weak sustainability approach that over-emphasises carbon targets, carbon removal and emissions reductions, from the land could have a negative impact on biodiversity, water resources, food production and human well-being.

Large-scale deployment of LMT could have a negative effect on resource poor communities and indigenous People's livelihoods and food security. For example, on a small scale, AR and bioenergy crops could provide new income opportunities for smallholder farmers. However, large-scale deployment of these LMTs could trigger large land use change and affect Indigenous People's land tenure and human rights violation and result in land grabbing and conflicts (Borelli *et al* 2019). The increased competition for land could lead, also, to higher food prices and an increased risk of hunger to the vulnerable people (Ahmed 2020b, Fujimori *et al* 2022). Therefore, before advancing for large-scale deployment, we need a better understanding of their impact on multiple local and national issues related to biodiversity, food security, water resources, economic well-being and, social and cultural value goals including the rights of Indigenous communities (Bonsch *et al* 2016, Stoy *et al* 2018, Fujimori *et al* 2022).

Women and, especially, those in resource-poor and low-income countries, could be even more negatively impacted by large-scale expansion of LMTs due to deeply entrenched institutional barriers. For instance, in some parts of the world where patriarchal societies are common, women have a submissive role in farming decisions about, for example, crop

choices and technology adoption (Gonçalves *et al* 2021). Women are consigned mostly to household duties and, in many societies, women are barred from land ownership (Gebrehiwot *et al* 2018), which impedes decision-making about LMT adoption. The increase in LMT implementation at the household level, particularly in lower-income countries, can increase burden on women already encumbered with household duties and work as unpaid farm labour for home.

Institutional mechanisms could help to close the gender inequality gap by ensuring land rights for women (Komjathy *et al* 2001) and enforcing recognition of Indigenous communities' land rights according to the United Nations Declaration on the Rights of Indigenous Peoples (UN 2007). Other deliberate actions should include promotion of inclusive decision-making, which would allow women and those facing marginalisation to be included in policy formulation, land management decisions and land use planning (Berger 2016), rather than being merely recipients of policy decisions. Women need adequate access to resources and legal ownership of such resources. Future studies should explore the impact of LMT implementation on women's empowerment and gender roles for accelerating transition to LMT. This would contribute to the construction of an international legal framework for rural women's rights, in the context of designing policies and programmes to promote large-scale deployment of LMTs.

6. Conclusions

LMTs have huge potential to contribute to emission reduction from land use and to carbon removal. AR, forest management, biochar and BECCS have the greatest potential among LMTs. However, many LMTs with lower mitigation potential provide greater co-benefits, including other environmental, social, cultural and economic benefits, climate adaptation and resilience at the local level. Giving too much emphasis to climate mitigation or carbon removal capacity using LMTs, without considering how the land could be used to address societal challenges and socioeconomic development goals, could exacerbate existing vulnerabilities of Indigenous People and marginalised farmers. Further research, adopting a system based approach, is necessary to consider all possible LMT portfolios, analyse the suitability and effectiveness of the different available options and identify carbon removal goals arising as co-benefits from interventions aimed at social improvements.

In this study, we provide a detailed two-level classification and analysis of the socio-cultural, technological, economic, institutional, and ethical barriers to adoption and scaling up of LMTs. Poor governance, lack of technology appropriate for local contexts, poor access to financial and technical support and,

lack of knowledge and awareness are critical barriers to implementing LMTs. These barriers can be addressed by appropriate policy environments, technical support, new financing mechanism, development of infrastructure and markets, and capacity building for good governance. Such efforts should avoid any negative consequences for already vulnerable smallholder farmers and Indigenous people.

Developing a novel integrated system approach, considering social and environmental goals for rapid scaling up of LMTs is critical. Large-scale deployment of LMTs requires replacement of traditional governance structures and mechanisms by new multi-sectoral and multilevel governance system, which ensures active and synergistic collaboration involving multiple stakeholders in planning and implementation of LMT interventions. An effective bottom-up and intercultural approach should take account of Indigenous knowledge, local values, cultural heritage and cultural interests and, provide less powerful stakeholders for co-decision making and empowerment opportunities. This would create an enabling environment for local innovations and new business development opportunities, to foster the large-scale promotion of LMTs. If planned and implemented appropriately (sustainably) through global efforts, LMTs could enable large-scale carbon removal and GHG emissions reduction and, also multiple co-benefits to satisfy socio-cultural, economic and environmental development goals at the local, national, and global level.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.


Acknowledgments

The authors thank the Land-use based Mitigation for Resilient Climate Pathways (LANDMARC) project partners, and all other stakeholders involved in the project, especially Indigenous and female stakeholders, who contributed valuable knowledge. We are extremely grateful to the case study leaders for their contributions: Eise Spijker (JIN Climate and Sustainability), Malte Renz (JIN Climate and Sustainability), Anke Benndorf (Öko-institut), Hannes Böttcher (Öko-institut), Rosalba Gomez (Universidad Nacional Experimental Francisco de Miranda), Annemarie Klaasse (eLEAF), Chelsea Greene (Innolab), Fengli Wang (Innolab), Stefan Bößner (SEI), Patricia Lourenco (Agroinsider), Federico Julian (AMBIENTA) and Thao Pham (CIAT). This study benefited from European Union Horizon 2020 research and innovation programme funding under Grant Agreement No. 869367 (LANDMARC). For additional work, the University of

Sussex's Higher Education Innovation Fund (HEIF) and Sussex Sustainability Research Programme (SSRP) provided further support through the CarbonMap Initiative for Sustainable Land Management (CARBONMAP) project and Linking Farmers with Carbon Markets (FARMCARBON) project.

ORCID iDs

Jenny Lieu  <https://orcid.org/0000-0002-9600-0501>

Moritz Laub  <https://orcid.org/0000-0003-2415-8067>

Bibiana Alejandra Bilbao  <https://orcid.org/0000-0001-9493-491X>

Francis X Johnson  <https://orcid.org/0000-0003-3597-8108>

References

- Abukari A and Abukari R 2020 Awareness of integrated soil fertility management practices in the Savelugu municipal of the northern region of Ghana *Rural Sustain. Res.* **43** 35–41
- Adevale C, Reganold J P, Higgins S, Evans R D and Carpenter-Boggs L 2018 Improving carbon footprinting of agricultural systems: boundaries, tiers, and organic farming *Environ. Impact Assess. Rev.* **71** 41–48
- Adolwa I S, Schwarze S and Buerkert A 2019a Impacts of integrated soil fertility management on yield and household income: the case of Tamale (Ghana) and Kakamega (Kenya) *Ecol. Econ.* **161** 186–92
- Adolwa I S, Schwarze S, Waswa B and Buerkert A 2019b Understanding system innovation adoption: a comparative analysis of integrated soil fertility management uptake in Tamale (Ghana) and Kakamega (Kenya) *Renew. Agric. Food Syst.* **34** 313–25
- Aggestam F, Konczal A, Sotirov M, Wallin I, Paillet Y, Spinelli R, Lindner M, Derks J, Hanewinkel M and Winkel G 2020 Can nature conservation and wood production be reconciled in managed forests? A review of driving factors for integrated forest management in Europe *J. Environ. Manage.* **268** 110670
- Ahmed J et al 2020a *Agriculture and Climate Change: Reducing Emissions through Improved Farming Practices* (McKinsey & Company)
- Ahmed J 2020b The effect of biofuel crops cultivation on food prices stability and food security *EurAsian J. Biosci.* **14** 613–21
- Ahmed S et al 2015 Economics of nitrogen and integrated weed management in dry seeded rice *J. Anim. Plant Sci.* **25** 1675–84 (available at: www.thejaps.org.pk/docs/v-25-06/24.pdf)
- Ai Z, Hanasaki N, Heck V, Hasegawa T and Fujimori S 2021 Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation *Nat. Sustain.* **4** 884–91
- Aragão L E et al 2020 21st century drought related fires counteract the decline of Amazon deforestation carbon emissions' *Nat. Commun.* **9** 536
- Armenteras D et al 2015 Red CYTED para el monitoreo del estado de la conservación y recuperación de bosques húmedos y secos en Latinoamérica en el contexto de la deforestación evitada. Síntesis de avances en la implementación de REDD+ en los países participantes de la Red IBERO REDD+ en América Latina *Red IBERO-REDD*
- Arora V K and Melton J R 2018 Reduction in global area burned and wildfire emissions since 1930s enhances carbon uptake by land *Nat. Commun.* **9** 1326

- Artz R R *et al* 2018 Peatland restoration—a comparative analysis of the costs and merits of different restoration methods *CXC Report* (Climate Exchange)
- Aryal K, Rijal A, Maraseni T and Parajuli M 2020 Why is the private forest program stunted in Nepal? *Environ. Manage.* **66** 535–48
- Astuti R and McGregor A 2017 Indigenous land claims or green grabs? Inclusions and exclusions within forest carbon politics in Indonesia *J. Peasant Stud.* **44** 445–66
- Austin K G, Baker J S, Sohngen B L, Wade C M, Daigneault A, Ohrel S B, Ragnauth S and Bean A 2020 The economic costs of planting, preserving, and managing the world's forests to mitigate climate change *Nat. Commun.* **11** 5946
- Babin A, Vaneckhaute C and Iliuta M C 2021 Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: a review *Biomass Bioenergy* **146** 105968
- Bahrs E and Angenendt E 2019 Status quo and perspectives of biogas production for energy and material utilization *Glob. Change Biol. Bioenergy* **11** 9–20
- Baig M B, Burgess P J and Fike J H 2021 Agroforestry for healthy ecosystems: constraints, improvement strategies and extension in Pakistan *Agrofor. Syst.* **95** 995–1013
- Baik E, Sanchez D L, Turner P A, Mach K J, Field C B and Benson S M 2018 Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States *Proc. Natl Acad. Sci.* **115** 3290–5
- Bains R 2015 *Economic Development in Jeopardy?: Implications of the Saik'uz First Nation and Stella' en First Nation V. Rio Tinto Decision* (Fraser Institute)
- Bashir O *et al* 2019 Soil organic matter and its impact on soil properties and nutrient status *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil* *Environ.* ed G H Dar *et al* (Springer) pp 129–59
- Bastin J-F, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner C M and Crowther T W 2019 The global tree restoration potential *Science* **365** 76–79
- Bavorová M, Unay-Gailhard Ī, Ponkina E V and Pilařová T 2020 How sources of agriculture information shape the adoption of reduced tillage practices? *J. Rural Stud.* **79** 88–101
- Bekchanov M, Mondal M A H, de Alwis A and Mirzabaev A 2019 Why adoption is slow despite promising potential of biogas technology for improving energy security and mitigating climate change in Sri Lanka? *Renew. Sust. Energ. Rev.* **105** 378–90
- Bellwood-Howard I R V 2014 Smallholder perspectives on soil fertility management and markets in the African green revolution *Agroecol. Sustain. Food Syst.* **38** 660–85
- Berger T 2016 Enhancing women's role in land management decisions *International Institute for Environment and Development* (available at: www.iied.org/enhancing-womens-role-land-management-decisions)
- Bilbao B, Leal A V and Méndez C L 2010 Indigenous use of fire and forest loss in Canaima National Park, Venezuela. Assessment of and tools for alternative strategies of fire management in Pemón indigenous lands *Hum. Ecol.* **38** 663–73
- Bilbao B, Mistry J, Millán A and Berardi A 2019 Sharing multiple perspectives on burning: towards a participatory and intercultural fire management policy in Venezuela, Brazil, and Guyana *Fire* **2** 39
- BMU 2019 *Aktionsprogramm Insektenschutz: Gemeinsam wirksam gegen das Insektensterben, Bundesministerium für Umwelt (Naturschutz und nukleare Sicherheit (BMU))*
- Bolan N *et al* 2023 Soil acidification and the liming potential of biochar *Environ. Pollut.* **317** 120632
- Bonsch M *et al* 2016 Trade-offs between land and water requirements for large-scale bioenergy production *Glob. Change Biol. Bioenergy* **8** 11–24
- Borelli S *et al* 2019 Agroforestry and tenure *Food and Agriculture Organisation* (available at: www.fao.org/3/ca4662en/CA4662EN.pdf)
- Bossio D A *et al* 2020 The role of soil carbon in natural climate solutions *Nat. Sustain.* **3** 391–8
- Bößner S, Devisscher T, Suljada T, Ismail C J, Sari A and Mondamina N W 2019 Barriers and opportunities to bioenergy transitions: an integrated, multi-level perspective analysis of biogas uptake in Bali *Biomass Bioenergy* **122** 457–65
- Böttcher H *et al* 2021 Options for strengthening natural carbon sinks and reducing land use emissions in the EU *Working paper. Hg* (available at: www.oeko.de/publikationen/p-details/options-for-strengthening-natural-carbon-sinks-and-reducing-land-use-emissions-in-the-eu)
- Brown B *et al* 2021 Understanding decision processes in becoming a fee-for-hire service provider: a case study on direct seeded rice in Bihar, India *J. Rural Stud.* **87** 254–66
- Bruun S, Jensen L S, Khanh Vu V T and Sommer S 2014 Small-scale household biogas digesters: an option for global warming mitigation or a potential climate bomb? *Renew. Sustain. Energy Rev.* **33** 736–41
- Bryan E, Ringler C, Okoba B, Koo J, Herrero M and Silvestri S 2013a Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? Insights from Kenya *Clim. Change* **118** 151–65
- Bryan E, Ringler C, Okoba B, Roncoli C, Silvestri S and Herrero M 2013b Adapting agriculture to climate change in Kenya: household strategies and determinants *J. Environ. Manage.* **114** 26–35
- Canadell J G and Schulze E D 2014 Global potential of biospheric carbon management for climate mitigation *Nat. Commun.* **5** 5282
- Caparrós A and Jacquemont F 2003 Conflicts between biodiversity and carbon sequestration programs: economic and legal implications *Ecol. Econ.* **46** 143–57
- Carlson K M, Goodman L K and May-Tobin C C 2015 Modeling relationships between water table depth and peat soil carbon loss in Southeast Asian plantations *Environ. Res. Lett.* **10** 074006
- Carrilho C D, Demarchi G, Duchelle A E, Wunder S and Morsello C 2022 Permanence of avoided deforestation in a Transamazon REDD+ project (Pará, Brazil) *Ecol. Econ.* **201** 107568
- Carter S, Manceur A M, Seppelt R, Hermans-Neumann K, Herold M and Verchot L 2017 Large scale land acquisitions and REDD+: a synthesis of conflicts and opportunities *Environ. Res. Lett.* **12** 035010
- Carton W, Asiyambi A, Beck S, Buck H J and Lund J F 2020 Negative emissions and the long history of carbon removal *WIREs Clim. Change* **11** e671
- Casagrande M *et al* 2016 Organic farmers' motivations and challenges for adopting conservation agriculture in Europe *Org. Agric.* **6** 281–95
- CCC 2020 Land use: policies for net zero UK (Committee on Climate Change) (available at: www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/)
- Chapman M, Walker W S, Cook-Patton S C, Ellis P W, Farina M, Griscom B W and Baccini A 2020 Large climate mitigation potential from adding trees to agricultural lands *Glob. Change Biol.* **26** 4357–65
- Chivenge P, Vanlauwe B, Gentile R, Wangechi H, Mugendi D, Kessel C and Six J 2009 Organic and mineral input management to enhance crop productivity in central Kenya *Agron. J.* **101** 1266–75
- Cobo S *et al* 2023 Sustainable scale-up of negative emissions technologies and practices: where to focus *Environ. Res. Lett.* **18** 023001
- Collins R D, de Neufville R, Claro J, Oliveira T and Pacheco A P 2013 Forest fire management to avoid unintended consequences: a case study of Portugal using system dynamics *J. Environ. Manage.* **130** 1–9
- Convention on Wetlands 2021 Global guidelines for peatland rewetting and restoration *Ramsar Technical Report No. 11*

- (Ramsar Convention Secretariat) (available at: www.ramsar.org/sites/default/files/documents/library/rtr11_peatland_rewetting_restoration_e.pdf)
- Cornelissen G, Pandit N R, Taylor P, Pandit B H, Sparrevik M and Schmidt H P 2016 Emissions and char quality of flame-curtain “Kon Tiki” kilns for farmer-scale charcoal/biochar production *PLoS One* **11** e0154617
- Creutzig F, Erb K-H, Haberl H, Hof C, Hunsberger C and Roe S 2021 Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments *Glob. Change Biol. Bioenergy* **13** 510–5
- Crowder D W and Reganold J P 2015 Financial competitiveness of organic agriculture on a global scale *Proc. Natl Acad. Sci.* **112** 7611–6
- Daigneault A, Baker J S, Guo J, Lauri P, Favero A, Forsell N, Johnston C, Ohrel S B and Sohngen B 2022 How the future of the global forest sink depends on timber demand, forest management, and carbon policies *Glob. Environ. Change* **76** 102582
- Falleiro R et al 2021 Histórico, Avaliação, Oportunidades e Desafios do Manejo Integrado do Fogo nas Terras Indígenas Brasileiras *Biodivers. Bras.* **2** 75–98
- DEFRA 2017 Agroforestry review, Department of Environment, Food and Rural Affairs, United Kingdom (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/868182/FOI2019_03038_Agroforestry_review.pdf)
- Dhalwal J K et al 2020 Medium-term impact of tillage and residue retention on soil physical and biological properties in dry-seeded rice-wheat system in north-west India *Soil Res.* **58** 468–77
- Dhyani S, Murthy I K, Kadaverugu R, Dasgupta R, Kumar M and Adesh Gadpayle K 2021 Agroforestry to achieve global climate adaptation and mitigation targets: are South Asian countries sufficiently prepared? *Forests* **12** 303
- Di Sacco A et al 2021 Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits *Glob. Change Biol.* **27** 1328–48
- Dickinson D, Balduccio L, Buysse J, Ronsse F, van Huylenbroeck G and Prins W 2015 Cost-benefit analysis of using biochar to improve cereals agriculture *Glob. Change Biol. Bioenergy* **7** 850–64
- Dixon R K 1995 Agroforestry systems: sources of sinks of greenhouse gases? *Agrofor. Syst.* **31** 99–116
- Do H, Luedeling E and Whitney C 2020 Decision analysis of agroforestry options reveals adoption risks for resource-poor farmers *Agron. Sustain. Dev.* **40** 20
- Doan T T, Sisouvanh P, Sengkhrua T, Sritumboon S, Rumpel C, Jouquet P and Bottinelli N 2021 Site-specific effects of organic amendments on parameters of tropical agricultural soil and yield: a field experiment in three countries in Southeast Asia *Agronomy* **11** 348
- Doelman J C et al 2020 Afforestation for climate change mitigation: potentials, risks and trade-offs *Globe Change Biol.* **26** 1576–91
- Donnison C, Holland R A, Hastings A, Armstrong L-M, Eigenbrod F and Taylor G 2020 Bioenergy with carbon capture and storage (BECCS): finding the win-wins for energy, negative emissions and ecosystem services—size matters *Glob. Change Biol. Bioenergy* **12** 586–604
- Duffy K A, Schwalm C R, Arcus V L, Koch G W, Liang L L and Schipper L A 2021 How close are we to the temperature tipping point of the terrestrial biosphere? *Sci. Adv.* **7** eaay1052
- Dynarski K A, Bossio D A and Scow K M 2020 Dynamic stability of soil carbon: reassessing the “Permanence” of soil carbon sequestration *Front. Environ. Sci.* **8** 514701
- Elahi E, Zhang H, Lirong X, Khalid Z and Xu H 2021 Understanding cognitive and socio-psychological factors determining farmers’ intentions to use improved grassland: implications of land use policy for sustainable pasture production *Land Use Policy* **102** 105250
- Essougong U P K, Foundjem-Tita D and Minang P A 2019 Addressing equity in community forestry: lessons from 20 years of implementation in Cameroon *Ecol. Soc.* **24** art9
- Fan L, Ge Y and Niu H 2022 Effects of agricultural extension system on promoting conservation agriculture in Shaanxi Plain, China *J. Clean. Prod.* **380** 134896
- FAO 2016 Forestry for a low-carbon future: integrating forests and wood products in climate change strategies *FAO forestry paper 177. Food and agriculture organisation* (available at: www.fao.org/3/i5857e/i5857e.pdf.)
- Farooq M, Siddique K H M, Rehman H, Aziz T, Lee D-J and Wahid A 2011 Rice direct seeding: experiences, challenges and opportunities *Soil Tillage Res.* **111** 87–98
- Flammini A, Brundin E, Grill R and Zellweger H 2020 Supply chain uncertainties of small-scale coffee husk-biochar production for activated carbon in Vietnam *Sustainability* **12** 8069
- Frank S, Gusti M, Havlik P, Lauri P, DiFulvio F, Forsell N, Hasegawa T, Krisztin T, Palazzo A and Valin H 2021 Land-based climate change mitigation potentials within the agenda for sustainable development *Environ. Res. Lett.* **16** 024006
- Fridahl M and Lehtveer M 2018 Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers *Energy Res. Soc. Sci.* **42** 155–65
- Fuglestvedt J, Rogelj J, Millar R J, Allen M, Boucher O, Cain M, Forster P M, Kriegler E and Shindell D 2018 Implications of possible interpretations of “greenhouse gas balance” in the Paris Agreement *Phil. Trans. R. Soc. A* **376** 20160445
- Fuhrman J, McJeon H, Doney S C, Shobe W and Clarens A F 2019 From zero to hero?: Why integrated assessment modeling of negative emissions technologies is hard and how we can do better *Front. Clim.* **1** 11
- Fujimori S et al 2022 Land-based climate change mitigation measures can affect agricultural markets and food security *Nat. Food* **3** 110–21
- Fuss S et al 2018 Negative emissions—part 2: costs, potentials and side effects *Environ. Res. Lett.* **13** 063002
- Fuss S and Johnsson F 2021 The BECCS implementation gap—a Swedish case study *Front. Energy Res.* **8** 553400
- Gebrehiwot M, Elbakidze M and Lidestav G 2018 Gender relations in changing agroforestry homegardens in rural Ethiopia *J. Rural Stud.* **61** 197–205
- Ghajar S and Tracy B 2021 Proximal sensing in grasslands and pastures *Agriculture* **11** 740
- Gnanavelrajah N, Shrestha R P, Schmidt-Vogt D and Samarakoon L 2008 Carbon stock assessment and soil carbon management in agricultural land-uses in Thailand *Land Degrad. Dev.* **19** 242–56
- Godde C M et al 2020 Soil carbon sequestration in grazing systems: managing expectations *Clim. Change* **161** 385–91
- Gonçalves C D B Q, Schlindwein M M and Carmo Martinelli G 2021 Agroforestry systems: a systematic review focusing on traditional indigenous practices, food and nutrition security, economic viability, and the role of women *Sustainability* **13** 11397
- Gong S, Hodgson J A, Tschamtk T, Liu Y, van der Werf W, Batáry P, Knops J M H and Zou Y 2022 Biodiversity and yield trade-offs for organic farming *Ecol. Lett.* **25** 1699–710
- Gosling E, Reith E, Knoke T, Gerique A and Paul C 2020 Exploring farmer perceptions of agroforestry via multi-objective optimisation: a test application in Eastern Panama *Agrofor. Syst.* **94** 2003–20
- Gough C, Garcia-Freites S, Jones C, Mander S, Moore B, Pereira C, Röder M, Vaughan N and Welfle A 2018a Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C *Glob. Sustain.* **1** 5
- Gough C, Mabon L and Mander S 2018b Social and ethical dimensions of BECCS *Biomass energy with carbon capture and storage (BECCS)* pp 251–76

- Gram G *et al* 2020 Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: a meta-analysis *PLoS One* **15** 0239552
- Grassi G *et al* 2021 Critical adjustment of land mitigation pathways for assessing countries' climate progress *Nat. Clim. Change* **11** 425–34
- Graves A *et al* 2017 Farmer perception of benefits, constraints and opportunities for silvoarable systems: Preliminary insights from Bedfordshire, England *Outlook Agric.* **46** 74–83
- Green D and Raygorodetsky G 2010 Indigenous knowledge of a changing climate *Clim. Change* **100** 239–42
- Gren I-M and Aklilu A Z 2016 Policy design for forest carbon sequestration: a review of the literature *For. Policy Econ.* **70** 128–36
- Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
- Gupta R *et al* 2011 *Conservation Agriculture for Sustainable Crop Production in Haryana* (Government of Haryana) p 125004
- Guteta D and Abegaz A 2016 Determinants of integrated soil fertility management adoption under annual cropping system in Arsamma watershed, southwestern Ethiopian Highlands *Afr. Geogr. Rev.* **35** 95–116
- Gutiérrez-Zamora V and Estrada M H 2020 Responsibilization and state territorialization: governing socio-territorial conflicts in community forestry in Mexico *For. Policy Econ.* **116** 102188
- Hajjar R *et al* 2021 A global analysis of the social and environmental outcomes of community forests *Nat. Sustain.* **4** 216–24
- Hanssen S V, Daioglou V, Steinmann Z J N, Doelman J C, Van Vuuren D P and Huijbregts M A J 2020 The climate change mitigation potential of bioenergy with carbon capture and storage *Nat. Clim. Change* **10** 1023–9
- Hansson A *et al* 2020 Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: the case of Tanzania *Environ. Dev. Sustain.* **22** 6851–75
- Harper R J, Sochacki S J and McGrath J F 2017 The development of reforestation options for dryland farmland in south-western Australia: a review *South. For.* **79** 185–96
- Harrison M E *et al* 2020 Tropical forest and peatland conservation in Indonesia: challenges and directions *People Nat.* **2** 4–28
- Haupt F and Lupke H 2007 Obstacles and opportunities for afforestation and reforestation projects under the clean development mechanism of the Kyoto protocol *Paper related to item 6, advisory committee on paper and wood products* (available at: www.fao.org/forestry/12713-0f8177c8e7d25bea8226c3e1c3240805a.pdf)
- Henderson B B, Gerber P J, Hilinski T E, Falcucci A, Ojima D S, Salvatore M and Conant R T 2015 Greenhouse gas mitigation potential of the world's grazing lands: modeling soil carbon and nitrogen fluxes of mitigation practices *Agric. Ecosyst. Environ.* **207** 91–100
- Hendroko S R *et al* 2015 The study of slurry recirculation to increase biogas productivity from *Jatropha curcas* *Linn Capsule Husk Two Phase Digestion Energy Proc.* **65** 300–8
- Hoang T T H, Do D T, Tran T T G, Ho T D and Rehman H U 2019 Incorporation of rice straw mitigates CH₄ and N₂O emissions in water saving paddy fields of Central Vietnam *Arch. Agron. Soil Sci.* **65** 113–24
- Horn J and Isselstein J 2022 How do we feed grazing livestock in the future? A case for knowledge-driven grazing systems *Grass Forage Sci.* **77** 153–66
- Howitt R *et al* 2013 Intercultural capacity deficits: contested geographies of coexistence in natural resource management: intercultural capacity deficits *Asia Pac. Viewp.* **54** 126–40
- Humpeöder F, Popp A, Dietrich J P, Klein D, Lotze-Campen H, Bonsch M, Bodirsky B L, Weindl I, Stevanovic M and Müller C 2014 Investigating afforestation and bioenergy CCS as climate change mitigation strategies *Environ. Res. Lett.* **9** 064029
- IPCC 2021 *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) (<https://doi.org/10.1017/9781009157896>)
- IPCC 2014 Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change ed O Edenhofer *et al* (Cambridge University Press)
- IPCC 2019 Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems ed P R Shukla *et al* (Cambridge University Press) p 896
- IPCC 2022 Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change ed P R Shukla *et al* (Cambridge University Press) (<https://doi.org/10.1017/9781009157926>)
- IPCC 2018 Global warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty ed V Masson-Delmotte *et al* (Cambridge University Press) p 616
- Jabłoński S J *et al* 2017 The influence of different pretreatment methods on biogas production from *Jatropha curcas* oil cake *J. Environ. Manage.* **203** 714–9
- Jain S *et al* 2019 *Global Potential of Biogas* (World Biogas Association) (available at: www.worldbiogasassociation.org/wp-content/uploads/2019/09/WBA-globalreport-56ppa4_digital-Sept-2019.pdf)
- Jat M L, Chakraborty D, Ladha J K, Rana D S, Gathala M K, McDonald A and Gerard B 2020 Conservation agriculture for sustainable intensification in South Asia *Nat. Sustain.* **3** 336–43
- Jew E K K *et al* 2020 Farming systems and conservation agriculture: technology, structures and agency in Malawi *Land Use Policy* **95** 104612
- Joosten H 2009 The Global Peatland CO₂ Picture: Peatland status and emissions in all countries of the world (Wetlands International) (available at: <https://unfccc.int/sites/default/files/draftpeatlandco2report.pdf>)
- Joosten H and Duene E V 2021 *Global guidelines for peatland rewetting and restoration Technical Report 11* (Ramsar)
- Jose S 2009 Agroforestry for ecosystem services and environmental benefits: an overview *Agrofor. Syst.* **76** 1–10
- Joseph S *et al* 2021 How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar *Glob. Change Biol. Bioenergy* **13** 1731–64
- Jouzi Z *et al* 2017 Organic farming and small-scale farmers: main opportunities and challenges *Ecol. Econ.* **132** 144–54
- Kalaba F K 2016 Barriers to policy implementation and implications for Zambia's forest ecosystems *For. Policy Econ.* **69** 40–44
- Kanowski P J, McDermott C L and Cashore B W 2011 Implementing REDD+: lessons from analysis of forest governance *Environ. Sci. Policy* **14** 111–7
- Karki L, Schleenbecker R and Hamm U 2011 Factors influencing a conversion to organic farming in Nepalese tea farms *J. Agric. Rural Dev. Trop. Subtrop.* **112** 113–23 (available at: www.jarts.info/index.php/jarts/article/view/2012011740355)
- Kay S *et al* 2019a Agroforestry is paying off—economic evaluation of ecosystem services in European landscapes with and without agroforestry systems *Ecosyst. Serv.* **36** 100896
- Kay S *et al* 2019b Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe *Land Use Policy* **83** 581–93
- Khatun K, Gross-Camp N, Corbera E, Martin A, Ball S and Massao G 2015 When participatory forest management

- makes money: insights from Tanzania on governance, benefit sharing, and implications for REDD+ *Environ. Plan A* **47** 2097–112
- Kim M-K, McCarl B A and Murray B C 2008 Permanence discounting for land-based carbon sequestration *Ecol. Econ.* **64** 763–9
- Kjerulf Petersen L and Andersen A H 2009 Socio-cultural barriers to the development of a sustainable energy system—the case of hydrogen *Research notes from NERI* p 248
- Komjathy K, Nichols S and Ericsson A 2001 Principles for equitable gender inclusion in land administration: FIG guidelines on women's access to land *Proc. FIG Working Week*
- Korhonen-Kurki K et al 2016 Coordination and cross-sectoral integration in REDD+: experiences from seven countries *Clim. Dev.* **8** 458–71
- Krause A et al 2017 Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators *Biogeosciences* **14** 4829–50
- Kreidenweis U et al 2016 Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects *Environ. Res. Lett.* **11** 085001
- Kumar V and Ladha J K 2011 Chapter six—direct seeding of rice: recent developments and future research needs *Advances in Agronomy* ed D L Sparks (Academic) pp 297–413
- Kurniawan T A, Othman M H D, Liang X, Goh H H, Gikas P, Chong K-K and Chew K W 2023 Challenges and opportunities for biochar to promote circular economy and carbon neutrality *J. Environ. Manage.* **332** 117429
- Kusnandar K, Brazier F M and Kooten O 2019 Empowering change for sustainable agriculture: the need for participation *Int. J. Agric. Sustain.* **17** 271–86
- Laganière J, Paré D, Thiffault E and Bernier P Y 2017 Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests *Glob. Change Biol. Bioenergy* **9** 358–69
- Lahmar R 2010 Adoption of conservation agriculture in Europe: lessons of the KASSA project *Land Use Policy* **27** 4–10
- Laing A M, Roth C H, Chialue L, Gaydon D S, Grünbühel C M, Inthavong T, Phengvichith V, Schiller J, Sipaseuth T, K and Williams L J 2018 Mechanised dry seeding is an adaptation strategy for managing climate risks and reducing labour costs in rainfed rice production in lowland Lao PDR *Field Crops Res.* **225** 32–46
- Lakitan B, Alberto A, Lindiana L L, Kartika K, Herlinda S and Kurnianingsih A 2018 The benefits of biochar on rice growth and yield in tropical riparian wetland, South Sumatra, Indonesia *Chiang Mai Univ. J. Nat. Sci.* **17** 111–26
- Lal R 1999 Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect *Environ. Prog.* **1** 307–26
- Lal R 2004 Soil carbon sequestration to mitigate climate change *Geoderma* **123** 1–22
- Lal R 2013 Enhancing ecosystem services with no-till *Renew. Agric. Food Syst.* **28** 102–14
- Lamers L P M et al 2015 Ecological restoration of rich fens in Europe and North America: from trial and error to an evidence-based approach *Biol. Rev.* **90** 182–203
- Larson A M et al 2013 Land tenure and REDD+: the good, the bad and the ugly *Glob. Environ. Change* **23** 678–89
- Lee M and Gambiza J 2022 The adoption of conservation agriculture by smallholder farmers in southern Africa: a scoping review of barriers and enablers *J. Rural Stud.* **92** 214–25
- Leifeld J et al 2019 Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100 *Nat. Clim. Change* **9** 945–7
- Leifeld J and Fuhrer J 2010 Organic farming and soil carbon sequestration: what do we really know about the benefits? *Ambio* **39** 585–99
- Leifeld J and Menichetti L 2018 The underappreciated potential of peatlands in global climate change mitigation strategies *Nat. Commun.* **9** 1071
- Lewis S L, Wheeler C E, Mitchard E T A and Koch A 2019 Restoring natural forests is the best way to remove atmospheric carbon *Nature* **568** 25–28
- Lindenmayer D B et al 2012 A major shift to the retention approach for forestry can help resolve some global forest sustainability issues *Conserv. Lett.* **5** 421–31
- Lipsett-Moore G J et al 2018 Emissions mitigation opportunities for savanna countries from early dry season fire management *Nat. Commun.* **9** 2247
- Lohani S P, Dhungana B, Horn H and Khatiwada D 2021 Small-scale biogas technology and clean cooking fuel: assessing the potential and links with SDGs in low-income countries—a case study of Nepal *Sustain. Energy Technol. Assess.* **46** 101301
- Lotter D 2015 Facing food insecurity in Africa: why, after 30 years of work in organic agriculture, I am promoting the use of synthetic fertilizers and herbicides in small-scale staple crop production *Agric. Hum. Values* **32** 111–8
- Lundin L, Nilsson T, Jordan S, Lode E and Strömberg M 2017 Impacts of rewetting on peat, hydrology and water chemical composition over 15 years in two finished peat extraction areas in Sweden *Wetl. Ecol. Manage.* **25** 405–19
- Lunt P H, Fyfe R M and Tappin A D 2019 Role of recent climate change on carbon sequestration in peatland systems *Sci. Total Environ.* **667** 348–58
- MacDicken K G, Sola P, Hall J E, Sabogal C, Tadoum M and de Wasseige C 2015 Global progress toward sustainable forest management *For. Ecol. Manage.* **352** 47–56
- Mackey B, Moomaw W, Lindenmayer D and Keith H 2022 Net carbon accounting and reporting are a barrier to understanding the mitigation value of forest protection in developed countries *Environ. Res. Lett.* **17** 054028
- Mahajan G and Chauhan B S 2015 Weed control in dry direct-seeded rice using tank mixtures of herbicides in South Asia *Crop Prot.* **72** 90–96
- Mahajan G, Chauhan B S and Gill M S 2013 Dry-seeded rice culture in Punjab State of India: lessons learned from farmers *Field Crops Res.* **144** 89–99
- Mahajan G, Chauhan B S and Johnson D E 2009 Weed management in aerobic rice in northwestern Indo-Gangetic plains *J. Crop Improv.* **23** 366–82
- Maillard É, McConkey B G and Angers D A 2017 Increased uncertainty in soil carbon stock measurement with spatial scale and sampling profile depth in world grasslands: a systematic analysis *Agric. Ecosyst. Environ.* **236** 268–76
- Matloob A, Khaliq A, Tanveer A, Hussain S, Aslam F and Chauhan B S 2015 Weed dynamics as influenced by tillage system, sowing time and weed competition duration in dry-seeded rice *Crop Prot.* **71** 25–38
- McElwee P 2023 Advocating afforestation, betting on BECCS: land-based negative emissions technologies (NETs) and agrarian livelihoods in the global South *J. Peasant Stud.* **50** 185–214
- Meng F, Qiao Y, Wu W, Smith P and Scott S 2017 Environmental impacts and production performances of organic agriculture in China: a monetary valuation *J. Environ. Manage.* **188** 49–57
- Meyer E L, Overen O K, Obileke K, Botha J J, Anderson J J, Koatla T A B, Thubela T, Khamkham T I and Ngqeleni V D 2021 Financial and economic feasibility of bio-digesters for rural residential demand-side management and sustainable development *Energy Rep.* **7** 1728–41
- Minasny B et al 2017 Soil carbon 4 per mille *Geoderma* **292** 59–86
- Minasny B, Sulaeman Y and Mcbratney A B 2011 Is soil carbon disappearing? The dynamics of soil organic carbon in Java *Glob. Change Biol.* **17** 1917–24
- Minx J C et al 2018 Negative emissions—part 1: research landscape and synthesis *Environ. Res. Lett.* **13** 063001
- Mistry J, Bilbao B A and Berardi A 2016 Community owned solutions for fire management in tropical ecosystems: case studies from indigenous communities of South America *Phil. Trans. R. Soc. B* **371** 20150174

- Mohan M *et al* 2021 Afforestation, reforestation and new challenges from COVID-19: thirty-three recommendations to support civil society organizations (CSOs) *J. Environ. Manage.* **287** 112277
- Morgan G W *et al* 2020 Prescribed burning in south-eastern Australia: history and future directions *Aust. For.* **83** 4–28
- Morgan K and Murdoch J 2000 Organic vs. conventional agriculture: knowledge, power and innovation in the food chain *Geoforum J. Phys. Hum. Regional Geosci.* **31** 159–73
- Mosquera-Losada M R *et al* 2018 Agroforestry in the European common agricultural policy *Agrofor. Syst.* **92** 1117–27
- Mucheru-Muna M W, Ada M A, Mugwe J N, Mairura F S, Mugi-Ngenga E, Zingore S and Mutegi J K 2021 Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya *Heliyon* **7** e06345
- Mulia R, Nguyen D D, Nguyen M P, Steward P, Pham V T, Le H A, Rosenstock T and Simelton E 2020 Enhancing Vietnam's nationally determined contribution with mitigation targets for agroforestry: a technical and economic estimate *Land* **9** 528
- Muneret L, Mitchell M, Seufert V, Aviron S, Djoudi E A, Pétillon J, Plantegenest M, Thiéry D and Rusch A 2018 Evidence that organic farming promotes pest control *Nat. Sustain.* **1** 361–8
- Muri H 2018 The role of large—Scale BECCS in the pursuit of the 1.5 °C target: an Earth system model perspective *Environ. Res. Lett.* **13** 044010
- Muthama D M, Tompkins E and Barry M 2019 Conflict between indigenous land claims and registered title: case studies from Canada and Kenya *Geomatica* **73** 15–27
- Myers R L 2007 Ecology: an integral part of fire management in cultural landscapes *Ecology: An integral part of fire management in cultural landscapes, Fourth Int. Wildfire Conf. 2007 (Seville, Spain)*
- Nair P, Kumar B M and Nair V 2021 *An Introduction to Agroforestry: Four Decades of Scientific Developments* (Springer) (<https://doi.org/10.1007/978-3-030-75358-0>)
- Nayak D *et al* 2015 Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture *Agric. Ecosyst. Environ.* **209** 108–24
- Neef A and Heidhues F 1994 The role of land tenure in agroforestry: lessons from Benin *Agrofor. Syst.* **27** 145–61
- Nemet G F, Callaghan M W, Creutzig F, Fuss S, Hartmann J, Hilaire J, Lamb W F, Minx J C, Rogers S and Smith P 2018 Negative emissions—part 3: innovation and upscaling *Environ. Res. Lett.* **13** 063003
- Niether W, Jacobi J, Blaser W J, Andres C and Armengot L 2020 Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis *Environ. Res. Lett.* **15** 104085
- Nousiainen D and Mola-Yudego B 2022 Characteristics and emerging patterns of forest conflicts in Europe—what can they tell us? *For. Policy Econ.* **136** 102671
- Nyong A, Adesina F and Elasha B O 2007 The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel *Mitig. Adapt. Strateg. Glob.* **12** 787–97
- OECD 2020 *Towards Sustainable Land Use: Aligning Biodiversity Climate and Food Policies* (OECD Publishing) (<https://doi.org/10.1787/3809b6a1-en>)
- Ogwu I, Omotesho O A and Muhammad-Lawal A 2018 Economics of soil fertility management practices in Nigeria *Food Systems Sustainability and Environmental Policies in Modern Economies* (IGI Global) pp 236–63
- Oldekop J A, Sims K R E, Karna B K, Whittingham M J and Agrawal A 2019 Reductions in deforestation and poverty from decentralized forest management in Nepal *Nat. Sustain.* **2** 421–8
- Ollinaho O I and Kröger M 2021 Agroforestry transitions: the good, the bad and the ugly *J. Rural Stud.* **82** 210–21
- Pan C, Shrestha A, Innes J L, Zhou G, Li N, Li J, He Y, Sheng C, Niles J-O and Wang G 2022 Key challenges and approaches to addressing barriers in forest carbon offset projects *J. For. Res.* **33** 1109–22
- Pasternak S 2022 Delgamuukw 25 years on: how Canada has undermined the landmark decision on Indigenous Land Rights, The Conversation (available at: <https://theconversation.com/delgamuukw-25-years-on-how-canada-has-undermined-the-landmark-decision-on-indigenous-land-rights-196196>)
- Paul C, Bartkowski B, Dönmez C, Don A, Mayer S, Steffens M, Weigl S, Wiesmeier M, Wolf A and Helming K 2023 Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation? *J. Environ. Manage.* **330** 117142
- Perosa B, Newton P and Silva R F B 2023 A monitoring, reporting and verification system for low carbon agriculture: a case study from Brazil *Environ. Sci. Policy* **140** 286–96
- Prichard S J *et al* 2021 Adapting western North American forests to climate change and wildfires: 10 common questions *Ecol. Appl.* **31** e02433
- Pulhin J M and Dressler W H 2009 People, power and timber: the politics of community-based forest management *J. Environ. Manage.* **91** 206–14
- Pumariño L, Sileshi G W, Gripenberg S, Kaartinen R, Barrios E, Muchane M N, Midega C and Jonsson M 2015 Effects of agroforestry on pest, disease and weed control: a meta-analysis *Basic Appl. Ecol.* **16** 573–82
- Raihan A, Begum R A, Mohd Said M N and Abdullah S M S 2019 A review of emission reduction potential and cost savings through forest carbon sequestration *Asian J. Water Environ. Pollut.* **1** 1–7
- Raimi K T 2021 Public perceptions of geoengineering *Curr. Opin. Psychol.* **42** 66–70
- Ramprasad V, Joglekar A and Fleischman F 2020 Plantations and pastoralists: afforestation activities make pastoralists in the Indian Himalaya vulnerable *Ecol. Soc.* **25** 1
- Ravikumar A *et al* 2018 Inter-sectoral and multilevel coordination alone do not reduce deforestation and advance environmental justice: why bold contestation works when collaboration fails *Environ. Plan. C* **36** 1437–57
- Regina K, Budiman A, Greve M H, Grönlund A, Kasimir Å, Lehtonen H, Petersen S O, Smith P and Wösten H 2016 GHG mitigation of agricultural peatlands requires coherent policies *Clim. Policy* **16** 522–41
- Robb S and Joseph S 2019 A report on the value of biochar and wood vinegar: practical experience of users in Australia and New Zealand; Australia New Zealand Biochar Initiative, Inc.: Tyagarah, Australia
- Roe S *et al* 2019 Contribution of the land sector to a 1.5°C world *Nat. Clim. Change* **9** 817–28
- Roe S *et al* 2021 Land-based measures to mitigate climate change: potential and feasibility by country *Glob. Change Biol.* **27** 6025–58
- Rosa L, Sanchez D L and Mazzotti M 2021 Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe *Energy Environ. Sci.* **14** 3086–97
- Rosillo-Calle F and Johnson F X 2010 *Food Versus Fuel: An Informed Introduction to Biofuels* (ZED books)
- Rumpel C *et al* 2022 The role of soil carbon sequestration in enhancing human resilience in tackling global crises including pandemics *Soil Secur.* **8** 100069
- Russell-Smith J, Monagle C, Jacobsohn M, Beatty R L, Bilbao B, Millán A, Vessuri H and Sánchez-Rose I 2017 Can savanna burning projects deliver measurable greenhouse emissions reductions and sustainable livelihood opportunities in fire-prone settings? *Clim. Change* **140** 47–61
- Rypdal K and Winiwarter W 2001 Uncertainties in greenhouse gas emission inventories—evaluation, comparability and implications *Environ. Sci. Policy* **4** 107–16
- Sahle M, Saito O, Fürst C and Yeshitela K 2018 Quantification and mapping of the supply of and demand for carbon storage and sequestration service in woody biomass and soil to mitigate climate change in the socio-ecological environment *Sci. Total Environ.* **624** 342–54

- Samaniego J *et al* 2021 Current understanding of the potential impacts of carbon dioxide removal approaches on the SDGs in selected countries in Latin America and the Caribbean *Final Report, Carnegie Climate Governance Initiative (C2G)/ Economic Commission for Latin America and the Caribbean (ECLAC)* (available at: https://repositorio.cepal.org/bitstream/handle/11362/47072/S2100426_en.pdf?sequence=1&isAllowed=y)
- Sánchez-Monedero M A, Sánchez-García M, Alburquerque J A and Cayuela M L 2019 Biochar reduces volatile organic compounds generated during chicken manure composting *Bioresour. Technol.* **288** 121584
- Sandalow D *et al* 2021 Biomass carbon removal and storage (BiRCS) roadmap *Biomass carbon removal and storage (BiRCS) roadmap: Innovation for cool earth forum (ICEF)*
- Santika T *et al* 2019 Heterogeneous impacts of community forestry on forest conservation and poverty alleviation: evidence from Indonesia *People Nat.* **1** 204–19
- Sapbamrer R and Thammachai A 2021 A systematic review of factors influencing farmers' adoption of organic farming *Sustainability* **13** 3842
- Sapkota T B, Jat R K, Singh R G, Jat M L, Stirling C M, Jat M K, Bijarniya D, Kumar M, Saharawat Y S and Gupta R K 2017 Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains *Soil Use Manage.* **33** 81–89
- Sardiana I K 2021 Organic vegetable farming system enhancing soil carbon sequestration in Bali, Indonesia *IOP Conf. Ser.: Earth Environ. Sci.* **724** 012025
- Schaafsma M, Beukering P J H and Oskolokaite I 2017 Combining focus group discussions and choice experiments for economic valuation of peatland restoration: a case study in Central Kalimantan, Indonesia *Ecosyst. Serv.* **27** 150–60
- Scheidel A and Work C 2018 Forest plantations and climate change discourses: new powers of “green” grabbing in Cambodia *Land Use Policy* **77** 9–18
- Schenck L 2018 Small Family Farming in Indonesia—A country specific outlook, family farming knowledge platform, Food and Agriculture Organisation of the United Nations (FAO) (available at: www.fao.org/family-farming/detail/en/c/1111082/)
- Schweizerisch Eidgenossenschaft 2020 Von welcher Bedeutung könnten negative CO₂-Emissionen für die künftigen klimapolitischen Massnahmen der Schweiz sein? Bericht des Bundesrates in Erfüllung des Postulates 18.4211 Thorens Goumaz vom 12., Dezember 2018 *Von welcher Bedeutung könnten negative CO₂-Emissionen für die künftigen klimapolitischen Massnahmen der Schweiz sein? Bericht des Bundesrates in Erfüllung des Postulates 18.4211 Thorens Goumaz vom 12*
- Scurlock J M O and Hall D O 1998 The global carbon sink: a grassland perspective *Glob. Change Biol.* **4** 229–33
- Serrano J, Shahidian S, Marques da Silva J, Paixão L, Carreira E, Pereira A and Carvalho M 2020 Climate changes challenges to the management of Mediterranean Montado ecosystem: perspectives for use of precision agriculture technologies *Agronomy* **10** 218
- Seufert V, Ramankutty N and Foley J A 2012 Comparing the yields of organic and conventional agriculture *Nature* **485** 229–32
- Shakoor A, Arif M S, Shahzad S M, Farooq T H, Ashraf F, Altaf M M, Ahmed W, Tufail M A and Ashraf M 2021 Does biochar accelerate the mitigation of greenhouse gaseous emissions from agricultural soil?—a global meta-analysis *Environ. Res.* **202** 111789
- Shin Y-J *et al* 2022 Actions to halt biodiversity loss generally benefit the climate *Glob. Change Biol.* **28** 2846–74
- Sierra C A, Crow S E, Heimann M, Metzler H and Schulze E-D 2021 The climate benefit of carbon sequestration *Biogeosciences* **18** 1029–48
- Silveira M L and Kohmann M M 2020 Chapter 3—maintaining soil fertility and health for sustainable pastures *Management Strategies for Sustainable Cattle Production in Southern Pastures* ed M Rouquette and G E Aiken (Academic) pp 35–58
- Skovsgaard L and Jacobsen H K 2017 Economies of scale in biogas production and the significance of flexible regulation *Energy Policy* **101** 77–89
- Smith O M *et al* 2019a Organic farming provides reliable environmental benefits but increases variability in crop yields: a global meta-analysis *Front. Sustain. Food Syst.* **3** 82
- Smith P *et al* 2013 How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* **19** 2285–302
- Smith P 2016 Soil carbon sequestration and biochar as negative emission technologies *Glob. Change Biol.* **22** 1315–24
- Smith P *et al* 2019b Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals *Annu. Rev. Environ. Resour.* **44** 255–86
- Soane B D, Ball B C, Arvidsson J, Basch G, Moreno F and Roger-Estrade J 2012 No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment *Soil Tillage Res.* **118** 66–87
- Somasundaram J *et al* 2020 No-till farming and conservation agriculture in South Asia—issues, challenges, prospects and benefits *Crit. Rev. Plant Sci.* **39** 236–79
- Sri Shalini S, Palanivelu K, Ramachandran A and Raghavan V 2021 Biochar from biomass waste as a renewable carbon material for climate change mitigation in reducing greenhouse gas emissions—a review *Biomass Convers. Biorefin.* **11** 2247–67
- Stoy P C *et al* 2018 Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales *BioScience* **68** 100–11
- Strack M, Davidson S J, Hirano T and Dunn C 2022 The potential of peatlands as nature-based climate solutions *Curr. Clim. Change Rep.* **8** 71–82
- Streffer J, Bauer N, Humpenöder F, Klein D, Popp A and Kriegler E 2021 Carbon dioxide removal technologies are not born equal *Environ. Res. Lett.* **16** 074021
- Tanneberger F, Appulo L, Ewert S, Lakner S, Ó Broilcháin N, Peters J and Wichtmann W 2021b The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives *Adv. Sustain. Syst.* **5** 2000146
- Tanneberger F, Couwenberg J, Dahms T, Gaudig G, Günther A, Kreyling J, Peters J, Pongratz J and Joosten H 2021a Towards net zero CO₂ in 2050: an emission reduction pathway for organic soils in Germany *Mires Peat* **27** 17
- Thapa G B and Rattanasuteerakul K 2011 Adoption and extent of organic vegetable farming in Mahasarakham province, Thailand *Appl. Geogr.* **31** 201–9
- Tiemeyer B *et al* 2020 A new methodology for organic soils in national greenhouse gas inventories: data synthesis, derivation and application *Ecol. Indic.* **109** 105838
- Torres A B, Marchant R, Lovett J C, Smart J C R and Tipper R 2010 Analysis of the carbon sequestration costs of afforestation and reforestation agroforestry practices and the use of cost curves to evaluate their potential for implementation of climate change mitigation *Ecol. Econ.* **69** 469–77
- Torres-Rojo J M, Moreno-Sánchez R and Mendoza-Briseño M A 2016 Sustainable forest management in Mexico *Curr. For. Rep.* **2** 93–105
- Torvanger A 2019 Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement *Clim. Policy* **19** 329–41
- Tschora H and Cherubini F 2020 Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa *Glob. Ecol. Conserv.* **22** 00919
- Tuinenburg O A, Bosmans J H C and Staal A 2022 The global potential of forest restoration for drought mitigation *Environ. Res. Lett.* **17** 034045

- Turner P A, Mach K J, Lobell D B, Benson S M, Baik E, Sanchez D L and Field C B 2018 The global overlap of bioenergy and carbon sequestration potential *Clim. Change* **148** 1–10
- UN 2007 United Nations declaration on the rights of indigenous peoples *UN Wash* **12** 1–18
- UNEP 2022a. Spreading like Wildfire—The Rising Threat of Extraordinary Landscape Fires *A UNEP Rapid Response Assessment*
- UNEP 2022b *Global Peatlands Assessment—The State of the World's Peatlands: evidence for action toward the conservation, restoration, and sustainable management of peatlands Main report* (Global Peatlands Initiative. United Nations Environment Programme)
- van Alphen K, van Ruijven J, Kasa S, Hekkert M and Turkenburg W 2009 The performance of the Norwegian carbon dioxide, capture and storage innovation system *Energy Policy* **37** 43–55
- Van Eck J and Waltman L 2010 Software survey: vOSviewer, a computer program for bibliometric mapping *Scientometrics* **84** 523–38
- Van Noordwijk M 2018 Agroforestry as part of climate change response *IOP Conf. Ser.: Earth Environ. Sci.* **200** 012002
- Vanlauwe B and Giller K E 2006 Popular myths around soil fertility management in sub-Saharan Africa *Agric. Ecosyst. Environ.* **116** 34–46
- Vera I et al 2022 Land use for bioenergy: synergies and trade-offs between sustainable development goals *Renew. Sustain. Energy Rev.* **161** 112409
- Verde S F and Chiaramonti D 2021 The biochar system in the EU: the pieces are falling into place, but key policy questions remain *Cadmus.eu* **792** 148161
- Walcott J et al 2015 *Mapping Multiple Benefits of REDD+ in Paraguay: Using Spatial Information to Support Land-use Planning* (UNEP-WCMC)
- Walker W S et al 2020 The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas *Proc. Natl Acad. Sci. USA* **117** 3015–25
- Wang W, Peng S, Liu H, Tao Y, Huang J, Cui K and Nie L 2017 The possibility of replacing puddled transplanted flooded rice with dry seeded rice in central China: a review *Field Crops Res.* **214** 310–20
- Wawire A W, Csorba Á, Tóth J A, Michéli E, Szalai M, Mutuma E and Kovács E 2021 Soil fertility management among smallholder farmers in Mount Kenya East region *Heliyon* **7** e06488
- Weerakoon W M W, Mutunayake M M P, Bandara C, Rao A N, Bhandari D C and Ladha J K 2011 Direct-seeded rice culture in Sri Lanka: lessons from farmers *Field Crops Res.* **121** 53–63
- Wichmann S 2017 Commercial viability of paludiculture: a comparison of harvesting reeds for biogas production, direct combustion, and thatching *Ecol. Eng.* **103** 497–505
- Wilkinson K 2020 The drawdown review, climate solutions for a new decade *The drawdown project*
- Williams B, Quilliam R S, Campbell B, Raha D, Baruah D C, Clarke M L, Sarma R, Haque C, Borah T and Dickie J 2022 Challenging perceptions of socio-cultural rejection of a taboo technology: narratives of imagined transitions to domestic toilet-linked biogas in India *Energy Res. Soc. Sci.* **92** 102802
- Williamson P 2016 Emissions reduction: scrutinize CO₂ removal methods *Nature* **530** 153–5
- Willott E 2004 Restoring nature, without mosquitoes? *Radioact. Ecol.* **12** 147–53
- Wilson G A and Hart K 2000 Financial imperative or conservation concern? EU farmers' motivations for participation in voluntary agri-environmental schemes *Environ. Plan A* **32** 2161–85
- Winiwarter W and Muik B 2010 Statistical dependence in input data of national greenhouse gas inventories: effects on the overall inventory uncertainty *Clim. Change* **103** 19–36
- Wollni M and Andersson C 2014 Spatial patterns of organic agriculture adoption: evidence from Honduras *Ecol. Econ.* **97** 120–8
- Wolske K S, Raimi K T, Campbell-Arvai V and Hart P S 2019 Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions *Clim. Change* **152** 345–61
- Woolf D, Amonette J E, Street-Perrott F A, Lehmann J and Joseph S 2010 Sustainable biochar to mitigate global climate change *Nat. Commun.* **1** 56
- Woolf D, Lehmann J and Lee D R 2016 Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration *Nat. Commun.* **7** 13160
- Xu Y 2018 Land grabbing by villagers? Insights from intimate land grabbing in the rise of industrial tree plantation sector in Guangxi, China *Geoforum J. Phys. Hum. Regional Geosci.* **96** 141–9
- Yang Q, Mašek O, Zhao L, Nan H, Yu S, Yin J, Li Z and Cao X 2021 Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation *Appl. Energy* **282** 116275
- Yang Y, Tilman D, Furey G and Lehman C 2019 Soil carbon sequestration accelerated by restoration of grassland biodiversity *Nat. Commun.* **10** 718
- Zetterberg L, Johnsson F and Möllersten K 2021 Incentivizing BECCS—A Swedish case study *Front. Clim.* **3** 685227