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

ENVIRONMENTAL RESEARCH
LETTERS

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RECEIVED
13 February 2023

REVISED
20 June 2023

ACCEPTED FOR PUBLICATION
13 July 2023

PUBLISHED
14 September 2023

TOPICAL REVIEW

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

Lokendra Karki[1,*], **Jenny Lieu**[2], **Maria Xylia**[3], **Moritz Laub**[4], **David Ismangil**[2], **Luis Virla**[2], **Eric Rahn**[5], **Bibiana Alejandra Bilbao**[6,7,16], **Siti Nurlaila Indriani**[8], **Pilar Martin Gallego**[9], **Afnan Khalil Ahmad Suleiman**[10], **Ruediger Schaldch**[11], **Takeshi Takama**[8], **José Rafael Marques da Silva**[12,13,14] and **Francis X Johnson**[15]

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, Universitätstrasse 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, Wilhelmshoeher 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

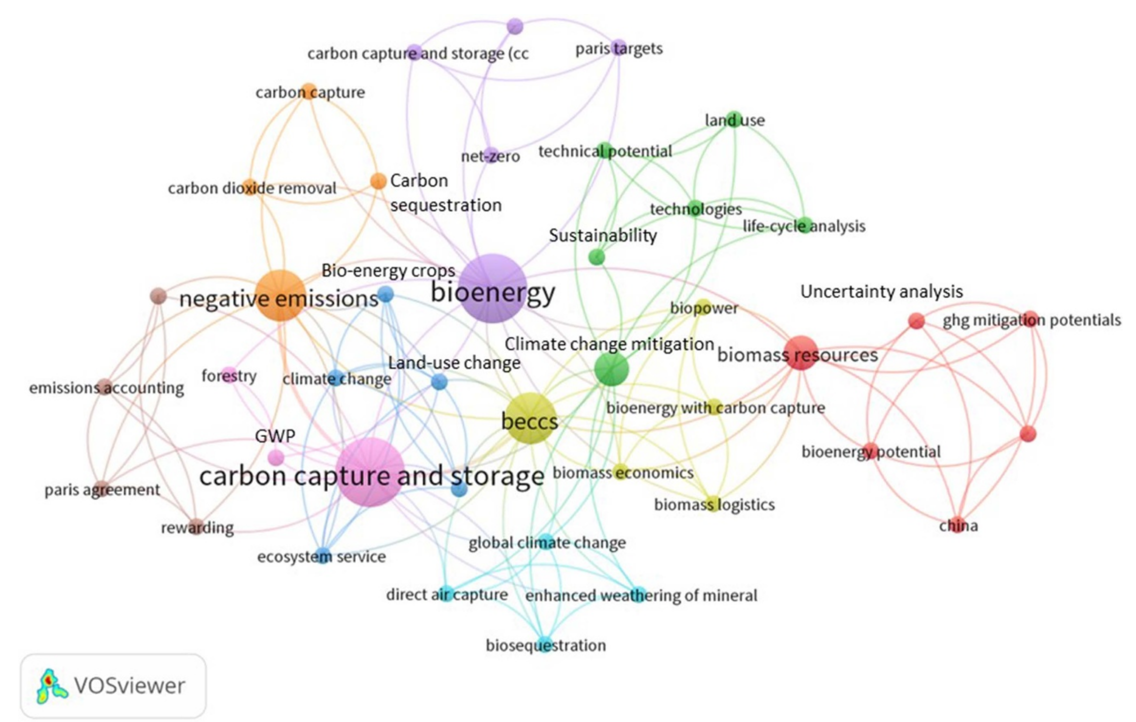

Figure 1. LMT bibliometric mapping of the articles reviewed. The search included various LMTs with 346 occurrences in total and grouped in focus areas by VOSviewer.

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 CO_2 e year^{-1}). Smith *et al* (2013) argue that supply-side land based mitigation solutions could offset around 1.5–4.3 Gt CO_2 e year^{-1} at a carbon price of 20–100 US$ t CO_2 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 CO_2 e year^{-1} (Smith *et al* 2013) and in the AR6 report (IPCC 2022), this increases slightly to 8–14 Gt CO_2 e year^{-1}. The estimates in Roe *et al* (2019, 2021) are even higher at 13–15 Gt CO_2 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 CO_2 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
	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)
Forestry	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)
	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_2e^{-1} in Vietnam (Mulia *et al* 2020), and economically feasible in Europe (Kay *et al* 2019b) and equal economic viablity 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_2e^{-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_2e^{-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_2e^{-1} (Fuss *et al* 2018), cheaper (58–77 US$ tCO_2e^{-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_2e^{-1} Europe, 0–7 US \$ tCO_2e^{-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_2e^{-1} global, 34–63 US \$ tCO_2e^{-1} tropics, 198–274 US \$ tCO_2e^{-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 $GtCO_2e$ 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 $GtCO_2e$ 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 CO2-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

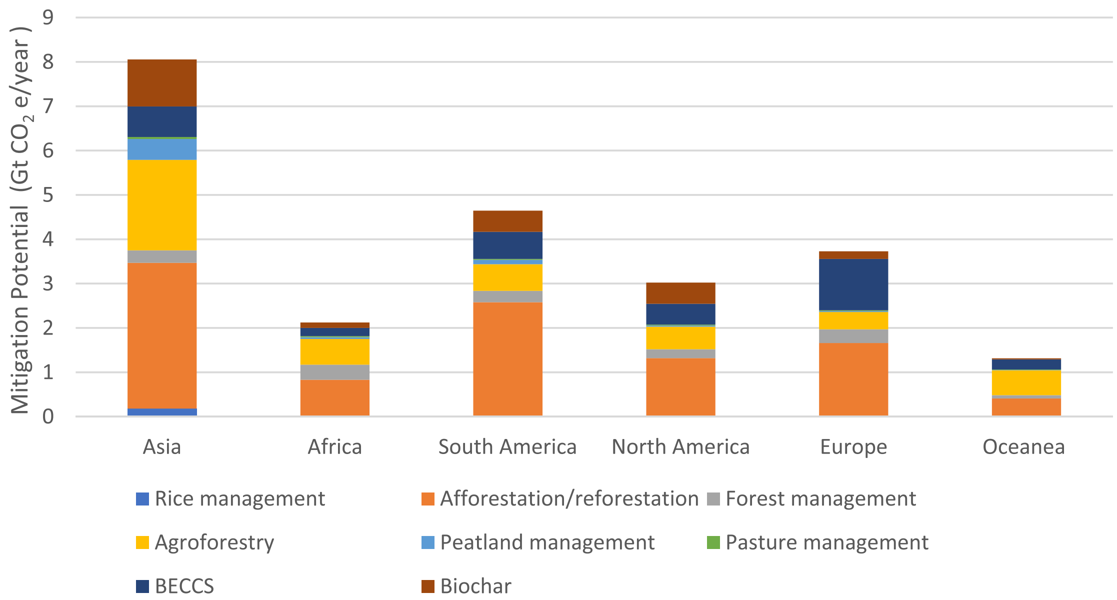

Figure 2. Mitigation potential of LMTs in different regions, Gt CO_2 e year^{-1}.
Source: Authors' estimation based on (Griscom *et al* 2017, Roe *et al* 2021).

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 *et al* 2021)
	Cultural affiliation to a traditional production system (cultural heritage) (Nyong *et al* 2007, Stoy *et al* 2018)
	Cultural norm (Guteta and Abegaz 2016, Sapbamrer and Thammachai 2021)
Knowledge and perception	Lack of knowledge (Tschora and Cherubini 2020, Lohani *et al* 2021, Mucheru-Muna *et al* 2021)
	Limited awareness of the value and benefits of LMT implementation (Gough *et al* 2018b, Lee and Gambiza 2022)
	Low social acceptance (Wolske *et al* 2019, Raimi 2021)
	Social pressure against LMTs (Bekchanov *et al* 2019, Williams *et al* 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 *et al* 2019, Fan *et al* 2022)
	A habit of relying on conventional practice (Vanlauwe and Giller 2006, Gupta *et al* 2011, Bilbao *et al* 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 BECCSs 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 *et al* 2016, Bilbao *et al* 2019)
	Requiring high management skills (Mahajan *et al* 2009, Soane *et al* 2012, Lamers *et al* 2015)
Resources	Difficulty in access to specialised machinery (Casagrande *et al* 2016, Jat *et al* 2020, Somasundaram *et al* 2020)
	Unavailability of transportation infrastructure (Guteta and Abegaz 2016, Turner *et al* 2018, Convention on Wetlands 2021)
	Lack of access to inputs (Ogwu *et al* 2018, Adolwa *et al* 2019b, Convention on Wetlands 2021)
	Limited/no access to credit (Bellwood-Howard 2014, Lohani *et al* 2021)
	Limited extension facilities (Thapa and Rattanasuteerakul 2011, Sapbamrer and Thammachai 2021)
Development	Lack of development of efficient monitoring, reporting and verification (Adewale *et al* 2018, Fuglestvedt *et al* 2018, Strefler *et al* 2021, UNEP 2022b)
	Large uncertainties about the benefits of an LMT (Creutzig *et al* 2021, Donnison *et al* 2020, Sandalow *et al* 2021, Yang *et al* 2021)
	Limited scientific understanding of land suitability (Baik *et al* 2018, Babin *et al* 2021)
	Technological readiness (Farooq *et al* 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 policymakers on technology. For example, some forest firefighters and other government institutions in Latin America are reluctanct 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 firefighting and protection agencies that have adequate knowledge of IFM implemented as LMT. For effective forest fire managment, 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 sequestrate 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 *et al* 2016, Flammini *et al* 2020, Jat *et al* 2020, Tanneberger *et al* 2021b)
	Large initial investment (Do *et al* 2020, Flammini *et al* 2020)
	Expensive to deploy at a scale where there is large potential (Smith 2016, Lohani *et al* 2021)
Income	Possibility of reduced income due to trade-offs (DEFRA 2017, Böttcher *et al* 2021, Sapbamrer and Thammachai 2021)
	Transitional period with higher production costs and lower income (Meng *et al* 2017, Soane *et al* 2012, Do *et al* 2020)
	Lack of incentives (Harper *et al* 2017, Wichmann 2017, Serrano *et al* 2020)
Value	Difficult to give value to the non-monetary benefits (ecosystem services) of LMTs (Donnison *et al* 2020, Kay *et al* 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 *et al* 2013b, Mosquera-Losada *et al* 2018, Verde and Chiaramonti 2021)
	Lack of policy implementation (Kanowski *et al* 2011, Kalaba 2016, Gough *et al* 2018a, Aryal *et al* 2020)
	Disinterest of policymakers (Haupt and Lupke 2007, Kalaba 2016, Harper *et al* 2017)
Governance	Lack of cross-sectoral responsibility-sharing (Korhonen-Kurki *et al* 2016, Rosa *et al* 2021)
	Top-down approach (Ravikumar *et al* 2018, Kusnandar *et al* 2019)
	Coordination between stakeholders (Jew *et al* 2020, Baig *et al* 2021)
	Lack of proper monitoring (Borelli *et al* 2019 UNEP 2022b)
Regulation	Counter-productive public policies and legislation (Myers 2007, Bilbao *et al* 2019, BMU 2019)
	Lack of standards and protocols to measure carbon sequestration (Torvanger 2019, Paul *et al* 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 *et al* 2017, Scheidel and Work 2018, Xu 2018, Hansson *et al* 2020)
	Issue of equitable benefit sharing (Khatun *et al* 2015, Essougong *et al* 2019)
	Issue of social conflicts (Hoang *et al* 2019, Santika *et al* 2019, Gutiérrez-Zamora and Hernández Estrada 2020)
Trade-offs	Land availability and competition with other land uses (Rosillo-Calle and Johnson 2010, Humpenöder *et al* 2014, Griscom *et al* 2017)
	Possible increase in food prices and compromise food security (Fuss *et al* 2018, Fujimori *et al* 2022, Gong *et al* 2022, Vera *et al* 2022)
	Negative effect on the environment (Kumar and Ladha 2011, Bonsch *et al* 2016, Williamson 2016, Babin *et al* 2021)
Fairness	Limited access of women and minority groups to resources and land (Astuti and McGregor 2017, Borelli *et al* 2019)
	No consideration of the rights of Indigenous People and local communities (Bilbao *et al* 2019, Walker *et al* 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. (Humpenöder *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 $GtCO_2$ 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 $GtCO_2$ 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 *et al* 2019, Tschora and Cherubini 2020, Dhyani *et al* 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 *et al* 2011, Mahajan *et al* 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 *et al* 2012, Jat *et al* 2020)
Integrated soil fertility management (ISFM)	Lack of favourable policy. Lack of appropriate infrastructure.	Credit support. Market development.	(Bryan et al 2013a, Bellwood-Howard 2014, Adolwa et al 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 *et al* 2018, Doan *et al* 2021, Joseph *et al* 2021, Verde and Chiaramonti 2021, Yang *et al* 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 *et al* 2017, Austin *et al* 2020, Doelman *et al* 2020, Mohan *et al* 2021)
Forest management	Need for long-term investment. Less income due to low wood harvest.	Continued grant or subsidy scheme support system.	(Torres *et al* 2010, Austin *et al* 2020, Böttcher *et al* 2021, Carrilho *et al* 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 *et al* 2018, Fridahl and Lehtveer 2018, Muri 2018, Wolske *et al* 2019, Donnison *et al* 2020, Fuss and Johnsson 2021, Rosa *et al* 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 *et al* 2019, Lohani *et al* 2021, Williams *et al* 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 *et al* 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 *et al* 2019, Falleiro *et al* 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 sequestrated 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 overemphasises 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 Managament (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

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