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A first stock take

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Capacity gaps in land-based mitigation technologies and practices: A first stock take

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ABSTRACT

Land-based mitigation technologies and practices (LMTs) reduce GHG emissions associated with land use and/or enhance terrestrial GHG sinks. This article investigates capacity gaps to successfully facilitate LMT adoption and/or scaling in the regions of Latin America, Europe, North America, sub-Saharan Africa and Southeast Asia. We look at LMTs such as agricultural land management, agroforestry, bioenergy with carbon capture and storage (BECCS), biochar, forest management, and peat/wetland management. We used a triangulation method based on literature review, an online survey, and semi-structured interviews with experts from Academia, Industry, NGOs, Local Communities and Government, to capture and analyze the most prominent capacity gaps by LMT and according to regional contexts. This approach identified 'understanding', 'awareness' and 'economic/finance' as the most important capacity gaps when it comes to LMT adoption and scaling across the aforementioned regions. A recommended first step for increased LMT adoption would be to address the knowledge and understanding capacity gaps, which, in turn, could help make LMTs more attractive to stakeholders. Policymakers in cooperation with other stakeholders might reflect on dedicated support policies and regulatory frameworks that level the playing field for LMTs (as compared to mitigation technologies and practices in energy and other sectors). Other good practice examples include market building for LMTs, using emerging carbon markets, designing bottom-up implementation plans in cooperation with local and Indigenous Peoples, increased ecosystems services payments and taking into consideration local and traditional knowledge for successful LMT adoption and scaling.

1. Introduction

According to the latest IPCC report, current mitigation measures by countries are likely insufficient to meet the aim of the Paris Agreement to limit the average global temperature increase to well below 2 °C (IPCC, 2022). Therefore, under a fairly wide range of future warming scenarios, a number of negative emission technologies to remove carbon from the atmosphere will need to be deployed at scale in order to maintain a chance of meeting a 1.5 °C or 2 °C warming target by the end of the century (IPCC, 2022) even though mitigation efforts (and demand side management) across all sectors and emission sources are needed.

Several promising options to reduce emissions and remove carbon from the atmosphere involve land-based mitigation technologies and practices, referred to as LMTs. LMTs are deliberate actions that either reduce the emissions of greenhouse gases (GHG) from land uses and/or remove greenhouse gases from the atmosphere and/or enhance land as a sink for GHGs while considering wider social-economic and environmental sustainability benefits. Despite no universally accepted categorisation, several technologies and practices have qualified as LMTs. Roe et al. (2021) provide a useful overview and categorize LMTs into **forest**

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LMTs, such as Afforestation, Reforestation or improved Forest Management; **agricultural LMTs,** such as Agroforestry, Manure Management or Biochar applications and **bioenergy LMTs,** such as Bioenergy production with carbon capture and storage (BECCS) (Roe et al., 2021). Peatland-, Wetland- and Mangrove Management are classified under forest LMTs but could be a category of their own. For our research, we grouped the LMTs into four main categories: *Forest Management* (afforestation, reforestation and fire management), *Agricultural Land Management* (agroforestry, reduced tillage, intercropping, organic agriculture, etc.), *Peatland & Wetland Management, Biochar, and Bioenergy & Carbon Capture and Storage* (BECCS). A more detailed description of the LMTs can be found in Annex A.

We also note that while some solutions, such as traditional forest management practices, have existed for centuries, especially in Indigenous Peoples' territories around the world (Bilbao et al., 2010), the recent interest in LMTs by academics and practitioners alike is relatively new. Given this novelty, many of the impacts LMTs could have on the environment, land, people, and climate are not sufficiently understood. For instance, evidence shows that biochar application to soils might increase the fertility of the soil under certain conditions (Kätterer et al., 2019, 2022; Schmidt et al., 2021), while some studies find that water retention potentials might be altered by biochar applications (Sohi et al., 2010). In addition, there is a huge variety in both the estimates of their greenhouse gas removal potential and their potential to offer socio-economic benefits to adopters (Ramirez-Contreras and Faaij, 2018; Karki et al., 2023). Moreover, LMTs are applied in a diverse set of contexts. For example, more sustainable forest management practices might be applied to Swedish pine forests or Colombian rainforests. Similarly, peatland restoration in the Netherlands might necessitate different approaches, skills and techniques than mangrove restoration in Thailand. However, one aspect most successful restoration efforts have in common is preventing any degradation processes that might negatively affect ecosystem health or land productivity.

To tailor LMTs to the diverse socio-cultural and biophysical contexts (e.g., Alpine mountains or South African savannahs), they require context-specific capacities for successful implementation. Adopters, therefore, are likely to face a variety of capacity gaps when wanting to implement or scale. However, unlike emerging research on the biophysical impacts of LMTs on land and climate adopter-centered investigation of capacity gaps is largely missing from the current debate.

The terms "capacity gaps" and "capacity needs" are mostly used in the international development context and often only in combination with terms like "capacity building" or "capacity development". Interestingly, capacity remains relatively undefined, even in a most recent special issue on capacity building in the context of climate change mitigation and adaptation (Klinsky and Sagar, 2022). Some scholars have tried to identify "capacity" as "[…] *the process by which individuals, organizations, institutions and societies develop abilities (individually and collectively) to perform functions, solve problems and set and achieve objectives"* (Stephen and Triraganon, 2009), while others point to the fact that capacity is context specific and dependent on the viewpoint of the stakeholder whose capacity is to be assessed or built (Eade, 2007; Kaplan, 2000). A simpler definition is given by Fowler et al. (1995): "*At its most general, capacity is the capability of an organization to achieve effectively what it sets out to do*" (Fowler et al., 1995).

Given the fuzziness of the term 'capacity' (and by extension the term capacity gap), we decided to adopt our own definition based on our literature review. The aim was to have an easy-to-understand definition, relatable and relevant to a diverse set of individual LMT stakeholders. Therefore, we defined *individual* capacity gaps as "*stakeholders experiencing insufficient capacities to adopt, implement and scale up a certain LMT.*" It is important to point out that in this definition, the stakeholder (an adopter, a policymaker or a provider/producer of LMTs) is at the centre. We were interested in their intrinsic, individual (in)capacity to adopt and scale LMTs and not so much in external and exogenous circumstances. For instance, the impacts of another recession or a global economic crisis would be a risk (external) while the individual capacity to access (or the inability to access) finance instruments for LMT adoption would be a capacity gap. That being said, we do not negate the importance of the external socio-economic contexts LMTs are usually embedded in, and we discuss external factors in this paper where appropriate or reflected upon by our engaged stakeholders (see methods section).

To our knowledge, this paper is the first attempt of such a capacity gap stock-taking not only systematically across a selection of key LMTs but also across several world regions. The insights gathered were part of a larger research project, LANDMARC, financed by the European Commission (Grant Agreement No. 869367). The knowledge presented here is expected to help design a better support framework for LMTs, which are of utmost importance to achieve internationally agreed-upon climate goals.

The paper is structured as follows: Section 2 describes our methodology, while Sections 3 and 4 present results from our triangulated information gathering approach (a literature review, a survey and a set of semi-structured interviews). Section 5 discusses our findings while Section 6 concludes the paper and gives some recommendations.

2. Methodology

Information presented in this article was obtained based on a triangulation approach (Patton, 1999), using a scoping literature review, followed by an online survey and a series of semi-structured interviews. These three sources of information helped us to gain a more comprehensive, richer understanding of the topic since each method has advantages and disadvantages. For instance, while literature usually provides the researcher with the latest science-based evidence, this evidence might not be entirely up-to-date with latest developments and/or may not account for the effects of particular contexts or regions, especially in an emerging research field such as the one of LMTs. In turn, interviews and group discussions may not always be supported by quantitative data or scientific evidence, but they are up-to-date and provide first hand stakeholder perspectives, sometimes not found in the literature.

As a first step, we conducted a scoping literature review which helped us to gain a first understanding of available information and potential categories of capacity gaps we could use for our analysis, a common approach in research (Munn et al., 2018). The literature review included 48 articles (the majority of them 43, peer-reviewed) discussing capacity gaps in the efforts to scale up LMTs worldwide (see Fig. 1).

We used key keyword searches on various scientific search engines, such as google scholar, Web of Science and Scopus, as well as general search engines like Google (examples include 'agroforestry + capacity' or 'biochar + capacity + gap') pertaining to our chosen LMTs and the snowballing technique where one source led to another to identify appropriate journal articles and grey literature. We then created a common MS Excel sheet and divided the sources amongst the research team (all co-authors), each researcher reviewing several sources and summarising their main insights. Based on this work, and after deliberation amongst the research team, we were able to draft a list of capacity gap indicator categories as described in Table 1.

Our second source of information was an anonymous survey, which we conducted online between November 2021 and February 2022. From 22 survey questions in total, 8 were open-ended questions while the rest were closed questions (see Annex D). We included our definition of capacity gaps to facilitate a common understanding of all survey respondents. Open questions were used so that respondents had the freedom to elaborate on some topics, but also to clarify the reasons behind their answers to the closed questions. It is important to note that not all survey questions are considered in this article since the survey also served as information gathering tool for other research tasks, not linked to the specific research questions of this study.

We used the extended professional network of consortium partners

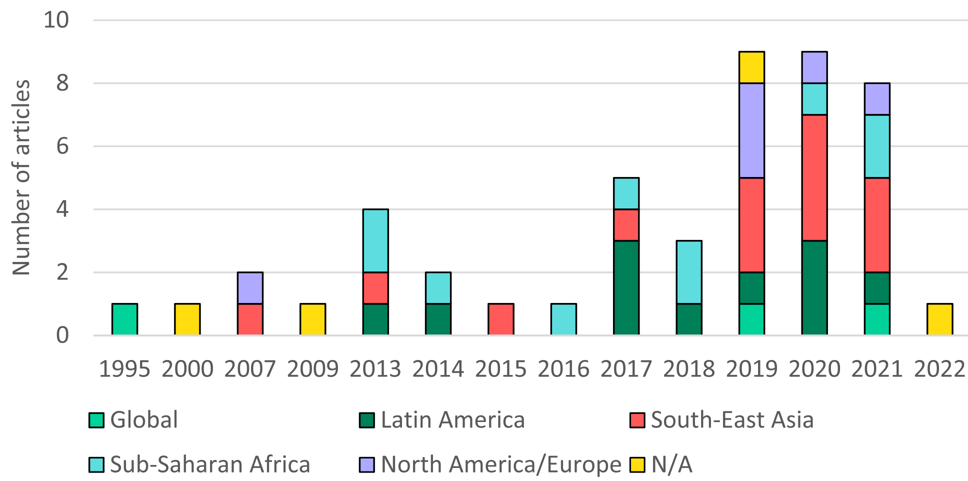

Fig. 1. Summary of reviewed literature per focus region and publication year.

Table 1
- Capacity Gap Indicators.

Indicator	Description
Awareness	The stakeholder is unaware of the LMT
Understanding	The stakeholder does not understand the LMT potential and its benefits
Skills	The stakeholder does not have the necessary skills to implement or scale the LMT
Finance/Economic	The stakeholder does not have the economic capacity or the financial support to implement the LMT
Implementation (policy)	The stakeholder does not have the capacity to adopt supportive policies for the LMT
Regulatory	The right regulatory and legal framework is not in place
Attitude	The stakeholder is critical of and/or opposing the LMT
Technical	The technology is not mature/adapted to the stakeholder's needs
Trade-Offs	The stakeholder encounters some trade-offs or opportunity costs when engaged in implementing/scaling the LMT.
Other	

(19 partner institutions working on land-based mitigation solutions, see acknowledgements) to identify appropriate experts who might be willing to answer our survey. In addition, professional social media channels such as LinkedIn were used to distribute the survey to potential respondents. In total, 64 respondents chose to answer our survey, a sample which turned out to be biased towards research professionals and academics (see Fig. 2). We are aware that this non-randomised respondent selection process is a potential limitation of our study. However, the broad knowledge of experts allowed us to gather valuable information for a first stock take. Moreover, considering the lack of knowledge on capacity gaps for LMTs, even a small and purposefully sampled survey can lead to meaningful and policy-relevant research results (Majchrzak, 1984).

Based on the insights of the literature review and the initial survey results, we chose to follow up on some specific issues by conducting 16 non-anonymous, semi-structured interviews, around 30–60 min in duration, consisting of 10 questions (see Annex C). Interview partners were specifically chosen to offset some of the potential biases from the survey. For instance, we were able to interview representatives from Indigenous Peoples in North America and some private sector stakeholders who were under-represented in our survey sample. Being mindful of the limitations of our approach, the following sections describe our insights.

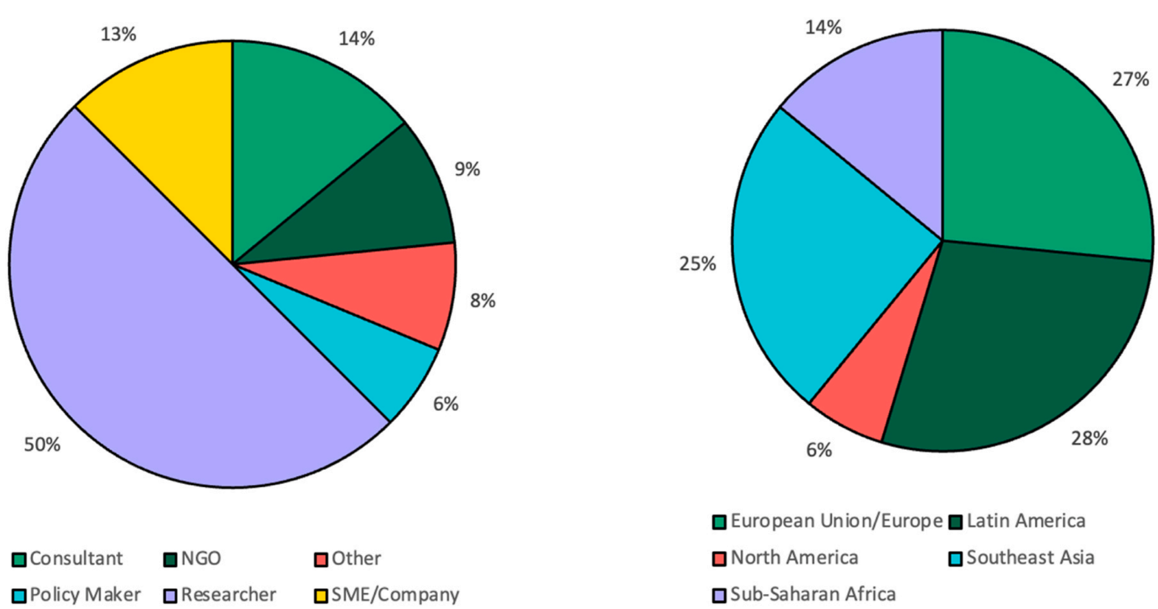

Fig. 2. Survey respondents distributed per stakeholder group (left) and region (right).

3. Capacity gaps in adoption and scaling LMTs

Based on reviewed literature sources, one of the most prominent capacity gaps was the (lack of) '**awareness**' of LMTs. Analysed sources show that a lack of awareness has been observed in biochar adoption (Guo et al., 2016; Latawiec et al., 2019) as well as in agroforestry practices in Vietnam (Simelton et al., 2017), Indonesia (Martini et al., 2017) and sub-Saharan Africa (Kalanzi et al., 2021). However, some scholars argue that some sustainable practices are (and have been) known for centuries by stakeholders such as Indigenous Peoples (Pichler et al., 2021) and might need to be brought back into the mainstream to make LMTs successful. Interestingly, awareness (or the lack thereof) can affect not only the LMT itself but also the socio-economic environment. For instance, a case study in Ireland showed that stakeholders were unaware of existing subsidy schemes for afforestation measures, which in turn hindered adoption (Duesberg et al., 2013). Quite logically, increasing awareness was found to increase adoption willingness of afforestation practices in Ireland (Duesberg et al., 2014).

The capacity gap '**understanding**' was also one of the most prominent capacity gaps described in the literature. While closely related to awareness, we believe that those terms are not interchangeable since stakeholders could be aware of a certain LMT but not understand its function or potential as a climate mitigation/adaptation strategy. This lack of understanding can relate to the biological processes determining carbon sequestration (Mucheru-Muna et al., 2021), thus failing to fully grasp the potential of LMT solutions (Tessema et al., 2020) or to a lack of understanding of how yields of lands used for LMT application and/or land use itself might change (Prestele and Verburg, 2020). Moreover, understanding the socio-cultural contexts impacting LMT adoption was deemed an important factor in two sub-Saharan Africa (SSA) case studies (Klauser and Negra, 2020; Owusu et al., 2021), while insights from the Philippines showed that a lack of understanding of practices such as chemical-free farming (Salazar, 2014) could hinder LMT uptake such as organic agriculture. Results from studies in Poland and Australia suggest that a lack of understanding in one sector and/or application might hinder (or help) the adoption of LMTs in another sector. In their study, (Latawiec et al., 2019) report that farmers familiar with the concept of sustainable agriculture were 16% more likely to adopt biochar, while an insufficient understanding of carbon markets was observed to hinder afforestation measures in Australia (Schirmer and Bull, 2014).

Since LMTs might, in some contexts, not be commercially attractive and/or unknown to stakeholders, the right '**implementation (policy)**' framework must be in place to support their uptake. This is, however, often not the case and therefore presents another capacity gap. Rosenstock et al. identified this lack of governance as an issue in the Global South, mentioning unclear land rights as a barrier (Rosenstock et al., 2019), while other studies argued that a lack of an appropriate legal framework would hinder effective Peat Land Management (Murdiyarso et al., 2019) and agroforestry practices (Samaniego et al., 2021). Lack of policy coherence was also an identified barrier in Indonesia (Martini et al., 2017; Carmenta et al., 2017) and a case study in SSA showed that households perceiving policies and their adopting institutions as effective and fair were 82% more likely to participate in forest restoration (Owusu et al., 2021). Another example is the implementation of fire suppression policies in Indigenous territories and protected areas (PAs) in Latin America, which forbade local, sustainable practices, thereby accumulating fuel and triggering the risk of more extensive and severe wildfires (Bilbao et al., 2010; Ponce-Calderón et al., 2021). While lacking governance mechanisms or frameworks could also be qualified as a risk since they are somewhat external to adopting stakeholders, such cases can represent a capacity gap when policy makers are lacking the capacity to adopt effective governance frameworks and/or regulations, a point made repeatedly in expert consultations (further discussion in Sections 4 and 5).

When it comes to '**finance/economic**' capacity gaps, many scholars identified the lacking profitability of several LMTs, such as BECCS (Ricardo Energy and Environment, 2020) or biochar (Scholz et al., 2014). However, economic circumstances often depend on the geographic, biophysical and socio-economic context, and market-driven economics is not an individual capacity gap. What has been described in the literature as a capacity gap, however, is not only the lacking knowledge of the economic benefits (Tsonkova et al., 2018) but also the absence of appropriate finance- and support instruments for LMT adoption in Africa (Klauser and Negra, 2020; Kalanzi et al., 2021), Southeast Asia (Bößner et al., 2019) or Latin America (Murdiyarso, Lilleskov, and Kolka, 2019; Samaniego et al., 2021). Interestingly, insights from Ireland suggest that even if a LMT would make sense from an economic perspective (i.e., it is profitable), the perception alone of it being too expensive might deter stakeholders from adopting it (Duesberg et al., 2013). In Kenya, research suggests that LMT adoption might be related to household income, with richer households being more willing to adopt an LMT, such as better natural resource management (Marenya and Barrett, 2007; Mucheru-Muna et al., 2021). These results suggest that income constraints rather than higher costs per se better define this capacity gap.

When it comes to '**technical capacity**' gaps, while the technologies and practices seem to be, theoretically, well-functioning and ready for market, studies showed that stakeholders might be unaware of the full technical carbon sequestration potential of LMTs (Gough and Mander, 2019), particularly in the Global South (Klauser and Negra, 2020). Also, stakeholders may not know about environmental impacts (Gough and Mander, 2019; Rosenstock et al., 2019), possibly due to a lack of available data (Klauser and Negra, 2020) (which was also suggested by our survey and interviews (see below)).

Little mention of capacity gaps related to '**skills**' (to implement and scale LMTs) was found during our review. We consider this outcome potentially related to our categorisation of capacity gaps and/or the overlaps with capacity gaps, such as *understanding*. Nevertheless, we observed some capacity gaps related to skills. Lacking the necessary administrative capacity was identified in a case study in Germany (Tsonkova et al., 2018), while managerial skills might be necessary to implement certain LMTs (Buyinza et al., 2020), thus showing the importance of training future LMT adopters (Bataille et al., 2016) which is often an overlooked capacity factor (Bößner et al., 2019).

Evidence for capacity gaps concerning '**attitude**' was illustrated from examples in Ireland, where (politically) conservative stakeholders reported to be less likely to implement LMTs such as afforestation (Duesberg, O'Connor, and Dhubháin, 2013). In contrast, two afforestation studies in sub-Saharan Africa suggested that stakeholders more concerned about the wellbeing of future generations (Schirmer and Bull, 2014) and about the intactness of forest ecosystem services (Owusu et al., 2021) were more likely to engage in afforestation activities. Evidence from Vietnam suggests that sometimes policymakers prioritise short-term economic gains over long-term sustainability concerns (Simelton et al., 2017). While this evidence remains anecdotal, it illustrates how attitudes and values might hinder or drive LMT uptake.

Finally, we identified '**trade-offs**' and opportunity costs as the hurdles adopters might face during LMT implementation and scaling. Schirmer and Bull (2014) argue that afforestation practices might reduce the flexibility to use land differently (Schirmer and Bull, 2014), while (Duesberg et al., 2013) point to the restriction on crop rotation of afforestation activities. (Bond et al., 2019) identified potential negative impacts of afforestation plans on wildlife and biodiversity, while (Cerbu et al., 2013) point to the trade-off between land for agricultural production vs land for re- and afforestation, which can even be a barrier for farmers to adopt agroforestry (Kalanzi et al., 2021). Similarly, (Prestele and Verburg, 2020) argue that in some cases, climate-smart agriculture might lead to lower-than-expected yields, especially for high-yielding crops or areas. However, time horizons also seem important here since short-term yield losses might be offset by longer-term, more fertile, productive soils in climate-smart agriculture or Agroforestry systems compared to high-use fertiliser monocultures (Franzen and Borgerhoff Mulder, 2007). Furthermore, approaches such as Climate-Smart Villages (CSV) that specifically include capacity building components might help to avoid productivity losses (Nabuurs et al., 2022).

4. A closer look at LMTs and regional perspectives: results from the survey and the interviews

Using the initial information gathered during the literature review, we conducted a survey and a series of semi-structured interviews to verify our initial insights and to get a better perspective on capacity gaps from different stakeholders in different regions. The survey and interview questions are available as supplementary material in the Annex. We present the results in a synthesizing rather than in a chronological manner. As one of the first steps, survey respondents were asked to rank capacity gaps from 1 (most important) to 10 (least important). Table 2 presents the ranking of each capacity gap; the smaller the average ranking, the higher the importance was perceived by the consulted stakeholders.

One can observe that 'understanding', 'finance/economic', 'skills' and 'awareness' were the most important capacity gaps across all regions (aggregated data) for all survey respondents combined. Although the sample was biased towards researchers (see methods section), it is interesting to note that for policy makers themselves, policy implementation was the number one capacity gap, while for SME/private sector respondents 'finance/economic' and 'regulatory' were deemed more important. Researchers identified 'finance/economic' but also 'understanding' and 'awareness' as top capacity gaps. Answers to the 'other' category included non-relevant information such as about solar PV. Therefore, 'other' was excluded from further analysis. The significant standard deviation is likely because the sample size was small (thus amplifying outliers), and the standard deviation is expressed for all LMTs combined, thus hiding some nuances per LMT. For instance, economic aspects are more important for more capital-intensive LMTs, such as BECCS, compared to less capital-intensive LMTs, such as Agricultural Land Management (see Fig. 3 below).

After this overall view, we decided to cut the data differently. Fig. 3 shows the capacity gaps related to each LMT. The following figure provides an overall picture of the most important capacity gaps per LMT identified by respondents.

Similar to the overall aggregated ranking in Table 2, **'finance/economic'** capacity gaps (and '**understanding**' were deemed the most prominent across LMTs but particularly for Peat- and Wetland Management, Biochar and BECCS. Answers given in the open question about capacity gaps described the absences of a high enough carbon price, of ecosystem service payments (especially in the forestry sector), and of adequate financial products for adopters to support LMT uptake (loans, credits etc.) as the main reasons why **economic** capacity gaps were so important. The economic capacity gap was deemed particularly true for more expensive LMTs such as BECCS, which had been assessed as not yet cost-competitive by an EU respondent. Lacking access to finance instruments was deemed especially relevant for the Global South, where identifying financial support or getting access to it was perceived as a barrier by survey respondents. This conclusion aligns with recent IPCC findings on financial barriers to land-based mitigation options (Nabuurs et al., 2022).

Four respondents to the survey made the connection between 'understanding' and 'finance/economic' capacity gaps, arguing that oftentimes, proper management plans and knowledge of how to make the best economic use of LMTs were lacking. Similarly, several survey respondents (particularly those taking the Agricultural Land Management perspective) argued that knowledge and understanding of appropriate financial instruments to adopt LMTs were missing. In addition, the lack of understanding of LMTS' economic and environmental potential as well as of their carbon sequestration potential (and the permanence thereof) was mentioned by respondents as a capacity gap. Related to this lack of understanding was also a lack of data availability on issues like permanence, storage potential and actual emissions savings according to respondents, particularly those who chose to describe Forest Management, Agricultural Land Management and Biochar. One stakeholder (Asia) argued that insufficient understanding was often linked to the socio-economic background of LMT adopters (lower educational and/or economic background would mean a lower adoption rate). Other respondents (US and Asia) pointed out that policymakers might also not understand LMTs sufficiently and would therefore be unable to adopt appropriate policies. One respondent (sub-Saharan Africa) argued that 'understanding' was always specific to geographical and socio-economic contexts, while another (Southeast Asia) argued that a lack of knowledge of how to engage the private sector would hinder LMT uptake. Respondents who chose to answer from the perspective of Agroforestry additionally mentioned that understanding how to design those agroforestry systems effectively would be lacking.

'Skills' related capacity gaps were deemed less important by respondents who chose to elaborate less specifically on that issue in the open question. However, oftentimes, skills were mentioned as part of the more important capacity gap of 'understanding' when respondents were prompted to explain their reasoning. For instance, respondents argued that policymakers might lack the skills to adopt adequate support frameworks and policies while accessing financial support (by not being able to navigate bureaucratic procedures) was one of the skills identified as a capacity gap for potential adopters.

When it comes to '**awareness',** respondents opined that adopters and policymakers were often unaware of either the LMT or its economic or environmental benefits especially when it comes to Peat and Wetland management. Similar to 'understanding', the need to be context specific when increasing awareness was mentioned. LMT providers (but also researchers) might need to listen better to potential adopters on the ground to be aware of their socio-economic context to provide LMTs that take into consideration local contexts and specificities. This might apply to all LMTs investigated.

As far as the capacity gap '**attitude'** is concerned, deemed comparatively less important, the 'not in my backyard' attitude hindering adoption was mentioned by respondents. However, one respondent (sub-Saharan Africa) stated that attitude was the most important capacity gap because if stakeholders did not have a positive attitude towards a certain technology or practice, all the other elements (appropriate policies, regulations, economic etc.) would not matter since buy-in by stakeholders would likely not happen. This respondent also argued that when stakeholders have a positive attitude towards an LMT, they would be much more eager and amenable to learning new practices, be more informed about LMT specificities and therefore would be much more likely to succeed when adopting LMTs.

Interestingly, '**policy/implementation'** and '**regulatory'** capacity gaps were deemed less important than attitude. However, as shown above, policy makers and stakeholders from the private sector deemed this capacity gap more important than those hailing from the research sector. Also, we observed a slight divergence between the open question

Table 2
- Ranking of Capacity Gaps from most important to least important, all regions and LMTs combined.

Rank	Gap	Average Ranking	Standard deviation
1	Understanding	3.80	2.29
2	Finance/Economic	3.82	2.47
3	Skills	4.55	2.25
4	Awareness	4.62	2.90
5	Attitude	5.00	2.43
6	Implementation (Policy)	5.06	2.19
7	Regulatory	5.15	2.55
8	Trade-Offs	6.22	2.44
9	Technical	6.44	2.91
10	Other	9.92	0.27

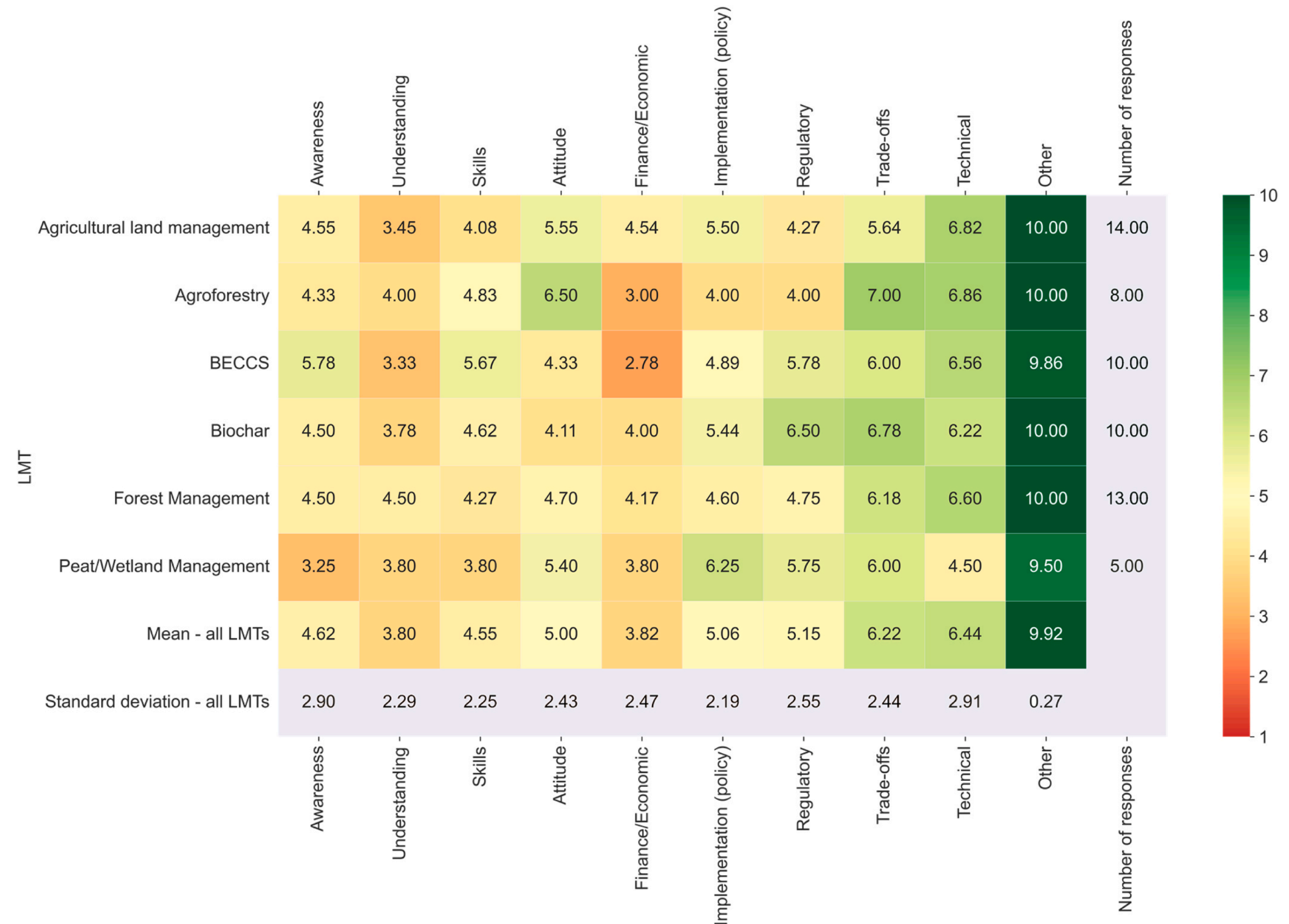

Fig. 3. – Ranking of perceived capacity gaps for each LMT. Number of responses per LMT, mean ranking, and standard deviation per capacity gap are included.

and the ranking exercise. While the ranking results suggest that policy- and regulatory capacity might be less important (compared to other gaps), several respondents mentioned lack of policy or support frameworks and a lack of regulation as the capacity gap in the open question, particularly for the LMT category of Agricultural Land Management and BECCS (for the EU). This is similar for Agroforestry, where three respondents argued that a lacking regulatory and incentive framework was a major capacity gap. Similarly, our expert interviews highlighted the need for supportive policy- and regulatory frameworks (see below). Also, for the Agroforestry LMT, a respondent (Latin American) mentioned the negative influence that Agri-businesses and their lobbying efforts might have on LMTs and policy making (without specifying). Interestingly, one respondent (EU) argued that LMT stakeholders might also suffer from over- and excessive regulation, hindering LMT adoption and scaling. While this might not be a capacity gap (strictly speaking) but more a risk, it nevertheless points to the fact that inappropriate regulation might negatively impact the capacity of stakeholders to adopt and/or scale up a certain LMT. However, from survey responses, it seems that the absence of a regulatory framework and the inexistence of proper economic incentive schemes are more important barriers to LMT uptake than overregulation and red tape.

‘Trade-offs’ as capacity gaps were identified relatively fewer times than other gaps. Adopting new agricultural practices such as no-tillage agriculture or deploying new products such as Biochar might lower economic returns for adopters in the short run since transitions might generate transaction costs or might be subject to a learning curve. One respondent (Southeast Asia) offered an interesting insight into how capacity gaps can not only be related to a specific technology but could also impact other technologies and practices. For instance, the increasing demand for agricultural products like palm oil or rubber in Southeast Asia led farmers to encroach on peatland/wetlands. However, because these soils usually have lower quality and yield, farmers will tend to cultivate more land to achieve the same level of production, thus exacerbating the shrinking of peat- and wetlands.

When it comes to **‘technological’** capacity gaps, we observed that only a few respondents had ranked this option as important. Moreover, while technological shortcomings or immature technologies might be better qualified as a risk than as a capacity gap, we nevertheless chose to keep that option to see whether respondents assessed the different LMTs as market ready, including logistics and appropriate infrastructure. Indeed, only for BECCS and Biochar were infrastructure challenges mentioned, namely the absence of storage and transport infrastructure for CO_2 in the BECCS case and uncertainties around the required continuous availability of feedstock for the case of biochar production, as argued by a respondent from the EU. We interpret this finding as LMT technologies being mostly “ready”, but socio-economic factors (and capacity gaps) hindering uptake and scale.

4.1. The regional perspective

After analyzing the survey data gathered through an LMT-focused lens, we investigated whether we could find regional differences in respondents’ capacity gap assessment. Besides cutting the data that way (see results in Fig. 4), we also used the semi-structured interviews to

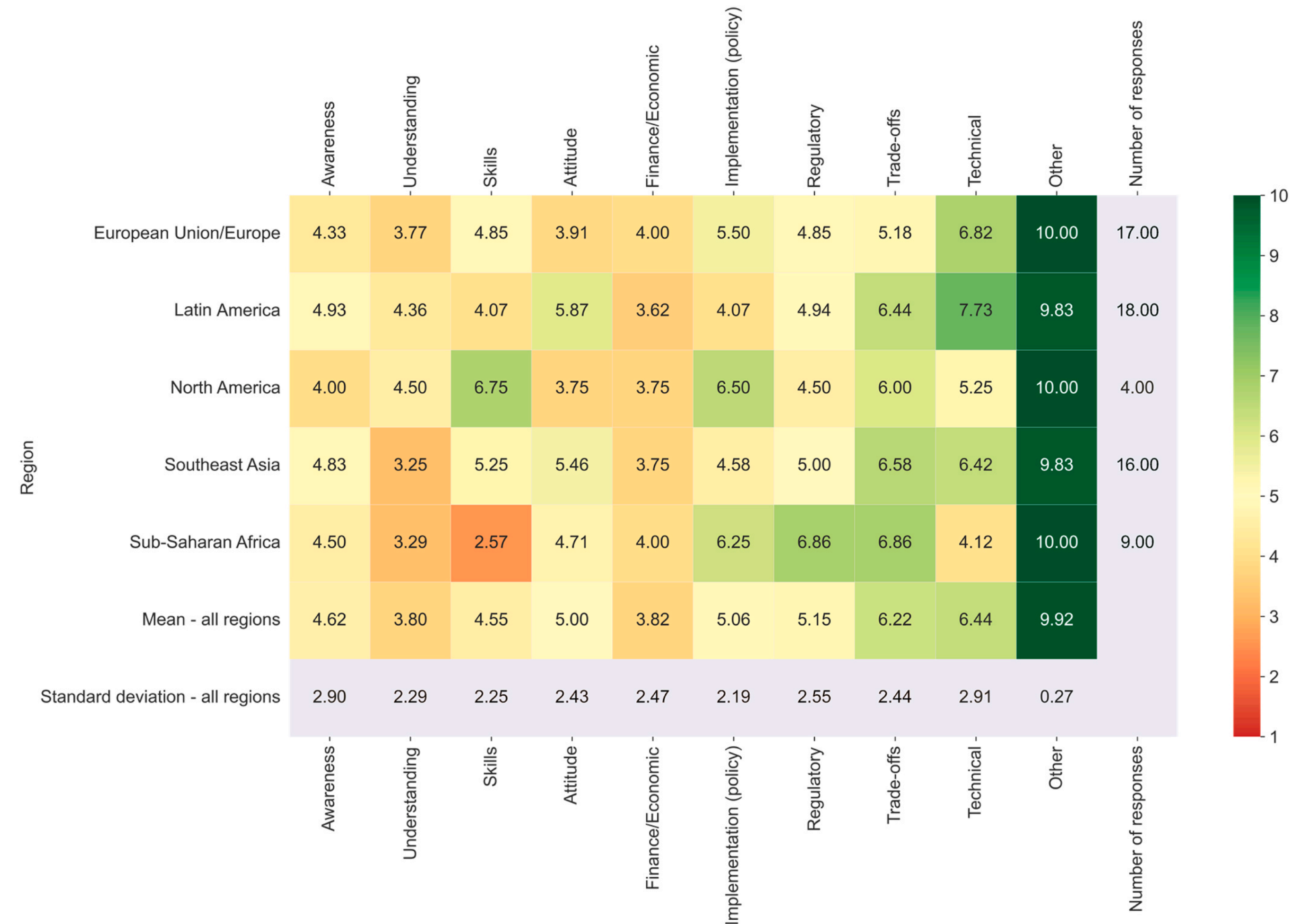

Fig. 4. – Ranking of perceived capacity gaps in each region as per survey respondents. Number of responses per LMT, mean ranking, and standard deviation per capacity gap are included.

complement our regional perspective. As mentioned in the methodology, we also sought to address the research-heavy bias in our survey sample by targeting experts from the private sector, the NGO sector and Indigenous Peoples. Moreover, while we asked interview partners about capacity gaps, a significant part of the interview also focused on getting the experts' opinions on overcoming those gaps.

Similar to the breakdown by LMT above (Fig. 3), capacity gaps related to '**understanding'** and '**financial/economic'** capacity gaps were deemed the most important capacity gaps across regions, with respondents taking a Southeast Asian and sub-Saharan African perspective arguing that 'understanding' was more important compared to the regional mean. Respondents who argued that understanding was important in sub-Saharan Africa mostly replied so from the perspective of Biochar and Agricultural Land Management, while most Southeast Asian respondents ranking 'understanding' high, discussed from the perspective of BECCS. While not aways specifying, overall semantic analysis suggests that most respondents took an adopter perspective and argued that adopters would not understand the impacts, challenges, and benefits of LMTs. Moreover, **'skills'** were deemed the most important capacity gap from a sub-Saharan perspective, even though the small sample might put this finding in perspective.

4.1.1. 'Understanding' as capacity gap from a regional perspective

One expert from **Southeast Asia** argued that the scientific community would need to provide more practical and easily understood protocols for the measurement and monitoring of carbon sequestration[1] since understanding of LMTs was still largely confined to the scientific community.[2] More in-field training and troubleshooting of each technology and practice would help adopters to implement LMTs (and increase understanding).[3] However, one expert cautioned that because issues like sequestration potentials and impacts of LMTs on soil fertility were still debated in the scientific community, it would be even more difficult for adopters to understand those issues.[4] Another expert (from an Indonesian perspective) echoed the insights of the survey when it comes to contexts: Since agricultural lands in Indonesia were usually individually owned, while forests and agroforestry were community-owned, different organizational modes might be needed for each LMT (catering to this difference in ownership) to achieve their potential.[5]

The experts assuming a **sub-Saharan African** perspective pointed to the need to increase understanding by educating and training farmers and forest managers, including on plant biology basics, since adopters would not be able to use solutions more in line with 'the principles of nature' if not knowledgeable about plant biology.[6] One way to achieve

[1] Expert No5
[2] Expert No6
[3] Expert No16
[4] Expert No8
[5] Expert No6
[6] Expert No9

that would be to establish cross-learning platforms to learn from other countries and their experiences.[7] Another expert noted that providing innovative 'extension services' such as platforms that facilitate learning between different farmer groups and that support value chain development would also increase understanding and awareness.[8]

Interviewed experts from **Latin America** thought that understanding of LMTs could be increased by avoiding silo thinking and by facilitating a cross-sectoral and cross-disciplinary approach between communities, researchers and policy makers.[9] The expert from Europe argued that the understanding of the carbon storage potential in the forestry sector was unclear, echoing arguments made from Southeast Asia. This lack of understanding was also mentioned by interviewed experts from the Indigenous Peoples in **North America,** who argued that better communication between the private sector, the government and the Indigenous Peoples about land- and forest management practices was needed,[10] while another North American expert spoke of the need to educate LMT professionals on 'carbon skills'(unspecified) and also pointed to need to avid silo thinking and to facilitate cross-sectoral learning.[11]

4.1.2. 'Finance/Economic' as capacity gap from a regional perspective

Regarding the capacity gap of **economic and financial** issues, this was deemed comparatively more of an issue in **Latin America** compared to other regions. However, the significant standard deviation (also due to a small sample size) makes such an interpretation rather anecdotal. Survey respondents from Latin America mostly adopted the perspective of Forest Management, Agroforestry, and Biochar, thus indicating some economic barriers to these technologies and practices.

Interviewed experts overall agreed with the survey results that economically, many of the LMTs are not yet profitable and argued that new markets for innovative products associated with LMTs were required. An interview partner from Latin America mentioned alcoholic beverages sourced from agave from agroforestry systems as an illustrative example of a marketable by-product which in turn might incentivise private sector players to buy into new LMTs.[12] Similarly, another expert from the region argued that biomass traders could function as intermediary actors between local land- and forest owners and help them to bring their produce to those international markets at scale.[13] We interpret this narrative as the need to find novel and creative by-products from LMT adoption, catering to international consumers and making them more attractive economically by insuring a steady revenue stream. In the same way, one expert argued that better certification schemes and awareness raising might lead to increased market demand.[14] Another suggestion to make LMTs more economically attractive was payments for ecosystem services, designed from the bottom up by and for local communities instead from the top down.[15] The need for LMTs to be adapted to local contexts as well as the importance of ecosystem service payments, were echoed by the expert from the **EU.**[16] Quite interestingly, one Latin American expert mentioned economies of scale as an important factor for overcoming the low profitability of LMTs.[17] This suggestion was echoed by experts from all the other regions (EU,[18] sub-Saharan Africa[19] and Asia[20]).

From a **North American** perspective, an expert from an Indigenous Peoples argued that people should take environmental damages caused by unsustainable Forest- and Land Management more into consideration (therefore making LMTs less costly when damages are priced in).[21] This was echoed by an expert from Latin America.[22] Another community expert argued that communal LMT ownership would increase the economic attractiveness of LMTs and suggested avoiding top-down implementation where voices from the communities and their needs would be ignored.[23] Another expert from North America argued for the role of carbon offset credits to increase the financial attractiveness of LMTs.[24]

Experts taking a **Southeast Asian** perspective reiterated the importance of scaling[25] and, in agreement with survey results, argued that carbon markets might be a potential source of revenues. However, the lack of baseline data and methodologies for monitoring, reporting and verification in carbon markets (MRV) was mentioned as a capacity gap[26] as well as the lack of carbon market regulation and policy. [27]

Experts interviewed from **sub-Saharan Africa** were slightly more positive about the economics of LMTs, particularly for Agroforestry systems. One expert pointed out that well-managed Agroforestry systems would offer several revenue streams such as wooden products or base materials for cosmetics or medicine.[28] Tapping into these value streams could be facilitated by larger learning- and business networks connecting the different stakeholders of the value chain.[29] That way, stakeholders having already adopted LMTs could offer management- and consultancy services to potential adopters to open up additional revenue streams.[30]

4.1.3. Access to Finance and Carbon Markets from a regional perspective

To understand how scaling of LMTs might be achieved, we asked interviewees about **access to financial products** that might support LMT uptake and received several suggestions.

One expert from **Southeast Asia** argued for the need of financial tools that focus on the long-term benefits for adopters,[31] such as blended finance instruments which do not only provide seed capital but also the capital for growth and scale.[32] Similarly, LMT projects could tap into private sector goals, i.e. companies' net zero strategies to leverage finance which would be difficult to access, particularly in the Biochar sector.[33] Another approach mentioned was to connect companies that work directly with farming communities to so-called sustainable impact investors who can provide the money but often have no knowledge about all the different LMTs.[34] Additionally, government support (i.e., subsidies and incentives) was identified as an additional funding source.[35]

From a **sub-Saharan Africa** perspective, one expert pointed to a structural problem of national- and donor policies, suggesting that many small-scale farmers are often not eligible to apply for financial support

[7] Expert No 9
[8] Expert No10
[9] Expert No11
[10] Experts No2&3
[11] Expert No4
[12] Expert No14
[13] Expert No14
[14] Expert No15
[15] Expert No15
[16] Expert No1
[17] Expert No 13
[18] Expert No1
[19] Expert No 9 &1 0
[20] Expert No7
[21] Expert No2
[22] Expert No11
[23] Expert No3
[24] Expert No4
[25] Expert No5
[26] Expert No8
[27] Expert No6
[28] Expert No9
[29] Expert No9 & 10
[30] Expert No9
[31] Expert No5
[32] Expert No7
[33] Expert No5
[34] Expert No8
[35] Expert No16

for their LMTs.[36] The other expert from the private sector, suggested that intermediary actors could use their involvement in large-scale projects to channel money to small-scale farming communities by leveraging their large network.[37] Here, the sub-Saharan Africa perspective agreed with the Southeast Asian perspective in arguing for the usefulness of intermediary actors who connect (and aggregate) small-scale LMT adopters to larger markets.

Experts from **Latin America** argued that awareness raising of negative externalities might incentivise financial providers to support LMTs (which could address these externalities)[38] An interesting remark came from expert No 15, who argued that many LMT practices and solutions would depend on local communities' knowledge and experiences, accumulated over generations. This knowledge would be largely untapped, and using it to scale LMTs would require much less financial support (i.e. it was deemed a low-hanging fruit) compared to projects implemented from the top down.[39]

The interviewees from **Europe** and **North America** preferred not to answer the question due to their self-proclaimed lack of expertise.

Since carbon markets had been identified in the survey as a potential instrument to make LMTs economically more attractive, the next question investigated how, in the absence of functioning carbon markets, LMTs could be made economically more attractive, particularly in low-income countries.

One expert from **Southeast Asia** mentioned that finance could come from net zero commitments by companies,[40] while another stakeholder mentioned restoration activities as a source of revenue without specifying how that could work.[41]

One expert from **sub-Saharan Africa** argued that not only below ground storage but also above ground biodiversity could be rewarded in monetary terms as an additional revenue stream for LMT adopters, thus speaking to the need for ecosystems services payments.[42] Another expert from sub-Saharan Africa echoed this, mentioning the need to tap into LMT's diverse value chains, such as using agricultural- or forest waste for Biochar or agricultural by-products not used by humans as animal feed.[43]

Experts from **Latin America** reiterated their support for payments for ecosystem services and multisectoral alliances and networks between adopters and other stakeholders to achieve the necessary scale as well as the need to utilise community and Indigenous knowledge to lower costs and make LMTs economically more attractive.[44]

4.1.4. 'Skills' as a capacity gap from a regional perspective

Survey respondents deemed capacity gaps concerning awareness, skills and attitude less important (see Fig. 4 above), with **skills** in particular considered less important as capacity gaps in North America and the EU. Most EU respondents adopted the Agricultural Land Management perspective. The interviews indirectly confirmed this ranking, and experts had been less vocal about those capacity gaps than understanding and economic capacity gaps.

When asked about skills specifically, the expert from **Europe** argued that small-scale forest owners would often not have the needed skills to manage forests more sustainably and/or as effective carbon sinks. External consultants and management service providers would usually bring in these skills. However, those service providers would sometimes not be aware of the latest development in more sustainable forest management practices.[45] The experts from an Indigenous People in **North America** emphasised the need for LMT implementing stakeholders to work together with the communities that are supposed to host LMTs to share skills and knowledge[46] (capacity building) but also for communities to translate their local knowledge into business opportunities[47] (pointing to the need for LMT skills to be transferred from one stakeholder group to another).

Experts from **Southeast Asia** argued that stakeholders would need user-friendly protocols and tools to understand the impacts of LMTs and their soil carbon qualities.[48] Regular training for adopters to introduce new technology, practice, and improvement is required to implement LMTs on a large scale.[49] From the perspective of **sub-Saharan African** experts, (lacking) long-term planning or LMT management skills were deemed a more important capacity gap than in other regions. One stakeholder argued that his company would offer such advisory services at a certain price to ensure user buy-in and ownership.[50] Another expert mentioned the key role that farmer group meetings played in creating co-learning platforms, which, ideally, could also be extended across borders to create truly regional knowledge and skills hubs where adopters could learn from each other's experiences.[51]

From a **Latin American** perspective, interviewees argued that a triangulation knowledge-sharing process between policy makers, adopters and academia would work to strengthen skills.[52] Another argument, reiterating previous statements, was that traditional knowledge would already be 'there' and that lacking skills, like the inability to access funding, were bureaucratic in nature.[53] Moreover, one expert pointed to the important role of trusted community leaders who could play a key role in skills transfer.[54]

4.1.5. 'Awareness' and 'Attitude' as capacity gaps from a regional perspective

Regarding **awareness** and **attitude**, four **Latin American** experts mentioned the importance of pilot projects – guided by researchers and experts - where communities could learn the benefits of new practices and technologies[55] especially in the (Agro) Forestry sector. Also, using diffusion campaigns in traditional- and social media, as well as adapting educational curricula including LMTs, was mentioned by one expert as one means to increase awareness.[56] Another interesting connection between a capacity gap and a potential solution came from an expert from **Southeast Asia** who argued that carbon offsets would not only increase the economic attractiveness of LMTs, but could help also to increase awareness: If people were to see the economic benefits of LMTs, they would 'pay attention' (and therefore get more informed about LMTs).[57]

4.1.6. Policy and Regulatory capacity gaps from a regional perspective

When asked about policy- and regulatory capacity gaps, the expert from **Europe** argued that besides supportive policies, red tape would also be an issue and that maybe just 'better' (unspecified) rules were needed.[58]

Interviewed experts from **North America** argued that policies were not advanced enough to restore ecosystems to their original state, that

[36] Expert No9
[37] Expert No10
[38] Expert No 11
[39] Expert No15
[40] Expert No5
[41] Expert No6
[42] Expert No9
[43] Expert No10
[44] Expert No13 & 15
[45] Expert No1
[46] Expert No2
[47] Expert No3
[48] Expert No5
[49] Expert No16
[50] Expert No9
[51] Expert No 10
[52] Expert No11
[53] Expert No12
[54] Expert No14
[55] Experts No11, 12, 13 & 14
[56] Expert No14
[57] Expert No7
[58] Expert No1

monitoring- and reporting provisions were not very clear, and that current policies would incentivise exploitation and not so much restoration.[59]

Experts from **Southeast Asia** gave an example that better land rights policies would be valuable in the Southeast Asian context, particularly for Forest Management. Moreover, more transparency facilitated by verification and certification (of carbon sequestraion etc.) was deemed important.[60] This aligns with the recent IPCC report on climate change, chapter 7 on AFOLU, which identifies monitoring, reporting and verification (MRV) as a key barrier (Nabuurs et al., 2022). One expert argued that a comprehensive policy framework for carbon markets was needed.[61]

One **sub-Saharan African** interviewee mentioned that policies in the forest sectors would use suboptimal metrics – such as a focus on simply planting trees rather than on long-term monitoring and management - while noting that policies to support the creation of LMT value chains would be needed.[62]

A **Latin American** expert argued that it was better to adopt incentivising policies instead of prohibitive ones - which oftentimes lack enforcement[63] - while another argued that clear guidelines for financing LMT projects should be established.[64] Another expert mentioned that, for instance, in Venezuela, many policies about land management and forestry had cross-cutting impacts across sectors, so all relevant stakeholders should be involved in the policy-making process.[65] Another suggestion was to include ecosystem services in financial accounting practices to make those services more visible.[66]

4.1.7. Technical readiness and trade-offs from a regional perspective

Insights from the regional interviews on the last two capacity gaps – **trade-offs** and **technological** capacity gaps – were again very much aligned with the survey results. The expert from the **EU** pointed to an important trade-off in the forestry sector between the exploitation of the forest economically or preserving the forest to increase (or maintain) biodiversity.[67] This trade-off might also be interpreted as diverging visions of stakeholders. For instance, a private forest owner might have a different vision of how to best use forest biomass than conservationists.

As mentioned in Section 3, technological capacity gaps were somewhat out of our scope since such gaps are not associated with the agency of individuals. However, we decided to confirm with interviewees whether they agreed (or disagreed) with the assumption that, overall, LMTs would be ready to be deployed at scale. However, that was mainly individual capacity gaps or the socio-economic environment that hindered LMT uptake and scale.

The interviewee from **Europe** confirmed that statement and argued that it was more a question of economics and unknow carbon sequestration potential that made adoption and scaling difficult.[68] Experts from **North America** agreed with the importance of considering socio-economic and cultural capacity gaps and argued for the need to form 'joint ventures' with local communities to overcome those.[69]

In **Southeast Asia**, one expert indicated that technological capacity gaps still existed (although elaborations were more pertaining to certification schemes),[70] while the other expert opined that some technological capacity was missing (although his remarks pertained more to a *knowledge capacity* gap like unknown carbon retention potential).[71]

One expert from **sub-Saharan Africa** interestingly pointed out that while changing to new agricultural or forestry practices was often perceived as a risk, sometimes not changing behavior and practices, e.g., continuing with degenerative practices such as "soil nutrient mining" without organic matter replenishment, would be an even bigger risk.[72] The other African expert argued that stakeholders in Africa often depend on knowledge transfer from other countries and continents which would not always translate into best practices locally due to diverging geographical but also socio-economic differences.[73]

Experts from **Latin America** mostly agreed with the statement pointing to the need for good policies, multisectoral alliances[74] and the need to listen to and engage with local [75] However, one expert argued that in decades of her work on those issues, badly designed technologies or technology not adapted to user needs was the main reason projects failed. She also argued that humans should not be treated as barriers or capacity gaps but as part of a resilient, holistic system that should analyse every angle of one project instead of providing top-down solutions that never worked. 1.[76]

5. Discussion

Our three-pronged approach to data and information gathering gave us insights into the capacity gaps for LMT deployment worldwide. To begin with, 'Understanding' and 'Finance/Economic' seem to be the most important capacity gaps stakeholders face when adopting (or wanting to adopt) and scaling LMTs. This finding is consistent across LMTs and regions (being mindful of the methodological limitations). When it comes to 'Understanding', four slightly nuanced knowledge gaps emerge. There is a lack of technical understanding in that some elements of LMTs, such as carbon sequestration potential or the permanence thereof, are not well known, especially outside (but even within) the scientific community. Moreover, adopters seem to lack an understanding of how to appropriately manage and implement LMTs, particularly if new practices and tools are needed. In addition, policy makers sometimes lack a sufficient understanding of how to adopt appropriate policies and regulatory frameworks to drive LMT scaling. Lastly, the knowledge of adopters on how to access financial support instruments for LMT adoption is lacking.

This is an essential aspect since the second most important capacity gap, as identified by our research, was related to the 'Finance/Economics' of LMTs. While not a capacity gap in a strict sense, survey respondents, literature review and interviews all pointed to the fact that LMTs still do not make much economic sense from the adopters' perspective in many contexts. Again, this finding was consistent across regions and LMTs. Reasons for this lack of economic attractiveness were manifold, like the lack of a sufficiently high carbon price, the absence of well-functioning carbon markets, trade-offs between goals such as biodiversity vs. exploitation of bioresources, the absence of eco-system service payments or the lack of additional revenue streams (and marketable products) associated with LMT implementation.

Similarly, the lack of 'Awareness' of existing support mechanisms for LMT adoption or additional sources of revenue LMTs often presents a barrier to LMT development. This lack of awareness is another capacity gap, surprisingly assessed as being more important in North America and the EU and more for the LMT Peat and Wetland Management.

59 Experts No 3&4
60 Expert No6
61 Expert No7
62 Experts No 9&10
63 Expert No 11
64 Expert No12
65 Expert No14
66 Expert No15
67 Expert No1
68 Expert No1
69 Experts No4&5
70 Expert No6
71 Expert No5
72 Expert No9
73 Expert No10
74 Expert No13
75 Expert No14
76 Expert No15

Moreover, this lacking awareness pertains to both the benefits (and challenges) of LMTs and their technological potential.

Closely ranked, but even before 'Awareness' was the capacity gap 'Skills'. For instance, adopting new practices and technologies usually necessitates learning new skills that stakeholders might not have and/or be unable to learn easily. Interestingly, this is true not only for the day-to-day business of LMT adoption, like the physical aspect of maintaining, for instance, an Agroforestry field but also to managerial capacities needed to manage and maintain LMTs economically. Similarly, and here the gap 'skills' joined gap 'awareness', insufficient (bureaucratic) skills to access financial support instruments was deemed a problem in LMT adoption, particularly in the Global South.

Interestingly, policies and regulatory capacity gaps were deemed relatively less important than for instance 'Understanding' and 'Finance/Economic' capacity gaps as far as the research community is concerned. This ranking was somehow different for stakeholders from the policy and private sectors who deemed policy and regulatory capacity gaps as more important. Interestingly, when prompted to elaborate on their rankings in an open question, survey respondents from all regions mentioned the importance of supportive policies as important for LMT adoption. Moreover, several respondents assessed the lack of policy- and regulatory frameworks as a capacity gap, thus putting the relatively low rank from the survey in perspective.

Lastly (and despite the diversity of respondents and regions investigated), from the perspective of survey respondents and interview partners, it seems to be the case that LMTs are, roughly speaking, 'ready' for market deployment, except for Peatland and Wetland Management. Even BECCS was deemed technologically ready even though two survey respondents mentioned the inadequate infrastructure (to store CO_2 for instance) as a hindering factor. This indicates that technologies and practices are ready to be deployed while barriers are likely more linked to adopters' individual capacity gaps and the socio-economic environment.

However, there is room for nuance. For instance, one interviewee pointed out that one should not blame only the adopter since poorly designed technologies that do not correspond to user needs and/or socio-economic or even geographical realities on the ground are equally to blame. Several survey respondents and interview partners echoed this need for LMTs to be (socio-economically and geographically) 'context specific', particularly in the Global South. From an LMT portfolio perspective, this represents a challenge since barriers to implementation and scale could vary between LMTs and between regions/countries, a fact that will require a variety of skills, strategies, and resources to be properly managed to address these needs. In addition, this could present some challenges for international cooperation since one-size fits all approaches might not yield the desired results.

Therefore, our findings highlight the need for approaches, strategies and solutions that consider regional specificities. Moreover, collaborative bottom-up approaches that leverage networks of learning for LMT implementation, scaling, as well as the development of supportive policies might be needed for LMTs to deliver on their climate mitigation and adaptation potential. It is therefore of utmost importance that LMT adoption and scaling is driven with adopting communities in mind and more from the bottom-up if they were to succeed, one of the main recommendations we suggest based on our research.

6. Summary and recommendations

Based on our findings and taking up many arguments made by our survey- and interview partners, we are able to give several recommendations.

The first step in facilitating increased LMT adoption and scaling would be to address the knowledge and understanding capacity gaps. Researchers and knowledge providers could supply more information, capacity building and science-based evidence to strengthen adopters' and other stakeholders' understanding of the carbon sequestration potential of LMTs and the permanence thereof. Moreover, in cooperation with service providers and private sector companies, they could offer guidance for some easy-to-use monitoring and verification methods for this sequestration potential. Policymakers could increase public awareness of LMTs by launching targeted information campaigns based on the most recent research findings using a variety of media channels. The adopting stakeholders might want to increase networked cooperation by establishing knowledge platforms and peer-to-peer learning clusters to exchange experiences from LMT adoption. Similarly, implementing pilot projects might facilitate this knowledge exchange and increase understanding.

This increased understanding might also help to make LMTs economically more attractive to stakeholders by using these knowledge platforms not only for knowledge sharing but also to exchange best practice examples and lessons learnt on managing LMTs effectively. Indeed, addressing the economic shortcomings is essential. In the absence of carbon markets at scale, discovering additional value streams in LMT systems is important, and here, some innovation and creativity might be needed to capitalise on by-products LMTs such as Agroforestry might have to offer. While this might seem easier in theory than practice, it is useful to remember that new market segments can emerge rather quickly depending on dietary trends. For instance, the import of Quinoa, a non-native crop in Europe, into the EU increased from 6000 tonnes in 2012–28,000 tonnes in 2019,[77] and anecdotal, localised evidence is emerging that consumers might be willing to shift consumer choices towards more sustainable products since the Covid-19 pandemic (Orîndaru et al., 2021; Accenture, 2020). Therefore, by-products of LMTs, especially in the Agriculture and Forestry sector, might indeed find some untapped markets in sustainability-minded middle-class households in OECD countries, as suggested by experts. Another option to make LMTs more attractive would be payments for ecosystem services and/or conservation or preservation efforts. Lastly, a useful suggestion from interview partners includes tapping into corporate social responsibility (CSR) and net zero commitments of private sector players who might be willing to finance LMTs and LMT adoption that way.

When it comes to skills and technological challenges, although the LMTs were deemed 'ready' in terms of technological maturity, lacking skills on how to implement, manage and scale them were identified as capacity gaps. Moreover, some LMTs such as BECCS or Biochar application would need a better infrastructure not only to store CO_2 in the BECCS case but also to set up efficient supply chains from the field (where the biomass is sourced) to the end user in the case of biochar, a supply chain that may not be well-developed. Here, the importance of pilot projects, peer-to-peer learning networks between academic stakeholders, private sector players and adopters were suggested to facilitate this infrastructure emergence but also an upskilling of potential adopters.

Regarding the policy sphere, policymakers, in cooperation with adopting stakeholders and the private sector, might reflect on dedicated support policies and regulatory frameworks that level the playing field for LMTs (as compared to traditional technologies and practices) by either providing start-up subsidies, other incentives such as tax rebates or by taking away support from harmful practices such as fossil fuel subsidies. Moreover, unbureaucratic access to financial support instruments could be facilitated along with dedicated policies focusing on start-up capital, growth, and long-term profitability. In addition, dedicated regulatory frameworks are needed for issues such as secure land rights. Regulatory and policy support frameworks are particularly relevant in the Global South, where those frameworks and access to finance are often lacking.

In addition to such top-down frameworks, it is also important to enrich these top-down policy- and market approaches with lessons

[77] https://www.cbi.eu/market-information/grains-pulses-oilseeds/quinoa-grains/market-potential

Table 3
- Overview of key capacity gaps and how to overcome them.

Capacity Gap	Reasons	How to address	Drivers
Understanding	• Lack of scientific understanding about impacts, benefits and challenges • Lack of understanding about LMTs by adopters	• Information campaigns • More interdisciplinary scientific research • Better MRV • Forming of peer-to-peer multi-stakeholder (scientist, policy-makers, adopters etc.) learning platforms and networks • Action-research and capacity building pilot projects	• Policy makers (information campaigns) • Adopters (learning networks) • Academia (more research for/on the design, implementation and socio-environmental impacts)
Finance/ Economics	• LMTs haven't reached scale yet • Lack of standardised and trustworthy certification methods • Insufficient price on carbon pollution • Few additional value streams and products from LMTs	• Discover new products and value chains from LMTs, especially in the agroforestry and forest systems • Aggregate output and bring to market • Payments for eco-system services • Carbon markets • Involve private sector ESG as source of finance • Rediscover traditional practices (low cost, low hanging fruit)	• Policymakers (put a price on carbon) • Private sector companies (use their CSR requirements to finance LMTs) • Consultancies and intermediary actors to link those CSR companies to LMT adopters • Local communities
Skills & Technical	• New technologies and practices need new skills • Lack of familiarity and training	• Peer-to-peer learning networks • Learning networks between academia, private and public sectors, local communities and adopters • Pilot interdisciplinary research-action projects • Capacity building	• Policy makers • Research community • NGOs and Think Tanks • Private sector • Consultancies
Awareness	• Little awareness of the existence of LMTs or what they can achieve	• Bottom-up strategies to empower local communities • Dedicated information campaign on media channels • Support dissemination programmes	• Policy makers • NGOs and Think Tanks
Attitude	• LMTs are unknown, benefits are unclear	• Pilot projects to show benefits • Information campaign to showcase benefits	• Policy makers • NGOs and Think Tanks • Avantgarde private sector companies
Implementation (Policy)/ Regulatory	• Lack of regulation • Lack of policy (support) frameworks • Red tape	• Dedicated support policies to facilitate take-off phase and scaling of LMTs • Facilitate access to finance and credit • Level playing field between LMTs and conventional technologies and practices	• Policy makers • NGO and Think Tanks (exercise pressure)

learnt from the bottom up. Many of the interviewed and survey experts argued that traditional knowledge on managing and scaling certain LMTs existed and continues to exist in the form of Indigenous knowledge and practice of local communities in surveyed regions. Listening to those local voices might prove to be a rather low-cost version of LMT adoption since some LMTs, like Agroforestry systems, have been practiced for many years. Moreover, as many experts noted, it is important to avoid one size fits all approaches and consider socio-economic and cultural contexts when designing and implementing LMTs in dialogue (rather than in 'monologue) with local host communities. Oftentimes, those local communities have a rather precise understanding of what they need but are often overlooked in the process of policymaking including designing, implementing, and scaling LMTs, which is neither sustainable for the communities nor the climate. Therefore, involving local communities and potential adopters more in the design- and decision making process of LMTs might facilitate quicker LMT uptake as encouraging examples of this participatory approach exist (Russell-Smith et al., 2017). Moreover, policy makers should be mindful of very localized barriers while the scientific community might provide policy makers with insights (and tools) on how to identify local barriers better. On a more abstract, less localized level, the following table provides a summary of key capacity gaps and how to address them (Table 3).

Lastly, our research has shown that several aspects of LMTs are rather poorly understood from a scientific perspective, which in turn contributes to the capacity gaps investigated in this paper. Although LMTs are somewhat complex to characterize and standardize due to the wide variation in their biophysical properties and functions, science-based evidence should nevertheless form the cornerstone of ambitious climate mitigation and adaptation action. Therefore, the scientific community might strengthen the knowledge base of LMTs, particularly in the Global South where case studies on impacts, benefits and challenges are still lacking. Policy makers might therefore want to support more pluri-disciplinary research projects on those matters. Of particular importance is knowledge about the carbon sequestration potential of LMTs, the impacts and trade-offs associated with LMTs in areas such as soil fertility, water retention and nutrient uptake, but also on the measurement and verification of those impacts. From a socio-economic perspective, more research is needed to investigate economic co-benefits of LMTs (e.g., yield, marketable by-products) while business studies and management studies could help identifying sound business models and good management practices of LMT systems.

CRediT authorship contribution statement

Stefan Bößner: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Maria Xylia:** Writing –

review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Bibiana Bilbao:** Writing – review & editing, Investigation, Formal analysis. **Siti N. Indriani**: Writing – review & editing, Investigation, Formal analysis. **Moritz Laub:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Eric Rahn:** Writing – review & editing, Investigation, Formal analysis. **Luis D. Virla**: Writing – review & editing, Investigation, Formal analysis. **Francis X. Johnson**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

Annex A. – Short description of investigated LMTs

Information and data about the following LMTs come from a literature review, carried out under a work package task of the Horizon Europe LANDMARC project (Grant Agreement No. 869367).

i. **Forest Management**

Afforestation and Reforestation

- *Definition: Afforestation is the process of establishing forest where there was previously no forest whereas reforestation is the process of replanting tree in previously forested area*
- ***Area:** Between 2000 and 2010, 94 Mha of tropical land has been reforested, but 139 Mha was deforested. 350 Mha of reforestation would help keep global warming to within 1.5 degrees. Potential of 678 Mha of land afforested and reforested in 2030.*
- ***Mitigation potential:** The potential carbon sequestration ranges from 0.1 to 2.6 GtCO2/yr, depending on the time period, and is highest in Africa and in tropical areas.*

Indigenous Peoples Fire Management

- *Definition: Indigenous Peoples fire traditional practices combined with modern prescribed burning method to suppress and/or prevent large fires in forest, savannas or grasslands. Mainly studied in Latin American countries and Australia.*
- ***Area:** Limited data globally. It is difficult to differentiate between wild and controlled fires through remote sensing.*
- ***Mitigation potential:** From 1997–2016, biomass burning from different ecosystems produced CO2 emissions equivalent to 23% of global fossil-fuel CO2. Global mitigation potential of fire management ranges from 0.16 to 0.41 Gt CO2 e/year*

i. **Agroforestry & Agricultural Land Management**

Reduced Tillage

- *Definition: Reducing or abandoning tillage offers a way to mitigate soil CO2 emissions*
- ***Area:** possibly 8.8% of arable land, although it may be much more.*
- ***Mitigation potential:** if reduced tillage was applied across Europe, sequestration potential of about 0.4 gigatons of C (1.5 gigatons of CO2 e. per year) until 2100 could be realized*

Agroforestry

- *Definition*: Trees are combined with crop- and/or animal husbandry on the same unit of land
- ***Area:*** 1 billion ha (Nair et al., 2009b)
- ***Mitigation and economic potential:*** Very diverse LMT; considering integration of different agricultural crops, shrubs and trees, as well as different kinds of livestock.

Organic Agriculture

- *Definition*: maintains soil fertility by returning organic material such as manures to the field and having crop rotations that include nitrogen fixing plants instead of mineral fertilizer.
- ***Area:*** global area under organic agriculture has been increasing, from 0.3% of arable land in 2000, to 0.8% in 2010 and 1.5% in 2019 (FiBL Statistics, 2019)
- ***Mitigation potential:*** uncertainty about the potential of organic agriculture to sequester CO2, especially over time.

i. **Peat & Wetland Management**

- *Definition*: Peatlands are carbon-rich wetlands formed from the reduced decomposition of vegetation biomass. Globally, peatlands are distributed across all continents. Peatlands are more widespread in Asia (38% of peatlands). Paludiculture is the carbon-neutral practice of crop production on wet and rewetted peatlands.

- ***Area:*** Europe and East Asia have the highest potential for implementing paludiculture, with degrading peatland areas of 220,000 km2 (in Russia, Belarus, Finland, Germany, Sweden, and Poland) and 200,000 km2 (Indonesia, China, Malaysia; Mongolia), respectively.
- ***Mitigation potential:*** rewetting of 1 km2 of peatland can result in a Global Warming Potential reduction corresponding to the emissions from ± 2600 average- sized petrol cars annually.

i. **Biochar**

- *Definition*: organic material synthesized through a pyrolysis process, by burning biomass with a high temperature and without oxygen. Applying biochar to soils can enhances soil carbon sequestration while also providing a variety of co- benefits for agriculture.
- ***Area:*** Could be applied on 500–900 million ha of land around the world, while estimated requirements for additional land for biomass to produce biochar range from 40 to 260 million ha
- ***Mitigation potential:*** IPCC special report (IPCC-SRCCL) noted a range of 0.5–2.0 GtC/year.

a. **Bioenergy and Carbon Capture and Storage**

- *Definition*: a series of technologies (a process) where biomass systems remove CO2 from the atmosphere and oceans, people harvest the energy through conversion, and the carbon is stored under the ground
- ***Area:*** Globally, 290–660 Mha for bioenergy crops are estimated to supply 1250 EJ/y
- ***Mitigation and economic potential:*** Globally, it is expected for BECSS to have a NET potential of 0.5–5 GtCO2/year, 3–8% of total energy consumption with a cost of 100–200 USD/tCO2. Large uncertainties remain around technical feasibility and governance.

Annex B. – List of interviewed stakeholders

Stakeholder Number	Affiliation	Region
Expert No1	County Administration Sweden	EU
Expert No2	Indigenous Community Elder, Canada	North America
Expert No3	Indigenous Community Representative & Sustainability Manager, Canada	North America
Expert No4	Peatland Scientist, Canada	North America
Expert No5	Green Invest Asia	Southeast Asia
Expert No6	Tropical Forest Alliance	Southeast Asia
Expert No7	Hasten Ventures	Southeast Asia
Expert No8	Olam Food Ingredients	Southeast Asia
Expert No9	L.E.A.F. Africa	Sub-Saharan Africa
Expert No10	Zero Two Heroes, Kenya	Sub-Saharan Africa
Expert No11	IPCC	Latin America
Expert No12	PREVFOGO (Brazil)	Latin America
Expert No13	Friends of Nature Foundation, Bolivia	Latin America
Expert No14	Universidad Nacional Experimental Francisco de Miranda	Latin America
Expert No15	UNESCO	Latin America
Expert No16	ASEAN Federation of Engineering Organisations	Southeast Asia

Annex C. – Interview Questions

1) (Preliminary) results of our survey point to the fact that LMT xxx is assessed with having the most carbon/emission reduction/removal potential. Do you agree with this observation? If so, could you explain why? Or if not, which would the LMT with the most potential be according to your expertise?
2) (Preliminary) results of our survey point to the fact that many stakeholders, particularly adopters, often do not sufficiently understand the benefits of certain LMTs or are not aware of them. Do you have any suggestions on how to **increase this understanding** amongst stakeholders?
3) Another key finding was that often, certain LMTs don't make **economic sense** from the perspective of the **adopter** (low revenues, low yield). Do you have any suggestions on how to make those LMTs **more economically attractive for adopters**?
4) The same might hold true for **private sector providers** of LMT technology. How could one increase the attractiveness of LMTs for private sector stakeholders (producers, financiers)? What kind of economic policies/instruments could be implemented to make the economics of certain LMTs more attractive?
5) Related to that question, one of the key capacity gaps identified were the lack of **financial capacity** of stakeholders. Even if a LMT makes economic sense, access to finance might be lacking. Do you have any suggestion how **finance providers** can better adjust their offer to LMT adopters?
6) In our survey, **carbon markets** have been mentioned a lot to play a supporting role in scaling LMTs. Do you agree? If so, could you explain the role of carbon markets a bit more in detail? If you disagree, could you please elaborate?
7) In the absence of a well-functioning carbon market/price on carbon, do you have any other idea how to make LMTs work economically, especially in developing countries?
8) From a regulator/policy perspective, **transparent rules and regulations** are often lacking and have been mentioned as capacity gaps. Do you have any suggestions on what kind of rules and regulations (i.e. the policy framework) need to be in place to support LMTs?

9) Another important capacity gap identified in the survey were **lacking skills** of adopters. Do you have any idea how one could increase the skill set of adopters to successfully adopt LMTs, particularly amongst stakeholders with little educational background?
10) Our survey suggests that technological capacity gaps are comparatively less important than socio-economic capacity gaps (i.e. the LMTs are technologically "ready" to be deployed at scale, but the human factor is the "problem"). Would you agree with this assessment? And if not, could you explain?

Annex D. – Survey Questions

1) What is your role (please choose the option that describes your role best)
2) Which region of the world would you say are you most experienced in?
3) In the region of the world you chose, what are the most promising LMTs in terms of Greenhouse Gas savings potential? Please rank them, with the first rank being the most promising LMT.
4) If you have chosen other, please describe the LMT and its emissions saving potential briefly
5) Please explain your ranking briefly.
6) In the region of the world you chose, what are the most promising LMTs in terms of economic potential? Please rank them, with the first rank being the most promising LMT.
7) If you have chosen other, please describe the LMT and its economic potential briefly
8) Please explain your ranking briefly.
9) We would like to know more about some specific LMTs. Please choose one of the following LMTs to assess in depth, depending on your own expertise.
10) When it comes to the chosen LMT, what do you think are the most important capacity gaps for regional stakeholders to implement the LMT? We define capacity gap as the insufficient capacity to adopt, implement or scale a certain LMT. Moreover, we are interested in the perspective of the following stakeholder groups: policy makers, adopters (i.e., people who will buy/implement the technology) and suppliers of the technology (companies, SMEs). When giving your answer, please indicate which perspective you chose
11) We have categorised several capacity gaps based on academic and grey literature. Could you please rank those capacity gaps (with regards to your chosen LMT). The gap you ranked highest is the most important one to overcome for the chosen LMT and the chosen perspective (policy maker, adopter or private sector actor/supplier of technology).
12) Please explain your ranking. You may focus on the top 3 capacity gaps.
13) When it comes to the chosen LMT, what do you think is needed to overcome the capacity gaps you were mentioning? How can adopters, policy makers and suppliers meet the capacity needs to fill the capacity gaps?
14) When it comes to delivering international climate and sustainability targets, which LMT would benefit from more research in order to understand its (socio-economic or emissions savings) potential or its capacity gaps better? You can choose several LMTs but please pick 3 at maximum.
15) Please explain your choice and what particular aspect of the chosen LMT should be more researched/better understood.
16) You as a stakeholder and expert, what LMT would you like to understand better/more in depth?
17) Thank you for your answers. In order to understand the issue of capacity gaps even better, would you be available for a follow-up interview (30–60 min) about capacity gaps and how to overcome them?

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