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A combination of top-down and bottom-up approaches in addressing major challenges of long-term socio-ecological research—the Taiwan experience

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Abstract

Long-term social-ecological research (LTSER) has been suggested to have high potential in providing insights and knowledge necessary for a sustainability transition. However, long-term and transdisciplinary, the core value of LTSER, remain major challenges. We describe how Taiwan LTSER addressed the two challenges through an approach that combines bottom up and top down processes. From the top-down, the funding agency categorized LTSER as a core facility like research vessels that monitors fundamental ecological and social drivers and indicators of the dynamics of the inter-linked and entangled social and ecological systems. From the top down, the funding agency established a LTSER program office which set criteria, highlighting that transdisciplinary is a pre-requisite for LTSER site selection. From the bottom up, scientists proposed potential LTSER sites based on their interest and each potential site formed a team that includes both natural scientists and social scientists. Thus, transdisciplinary research is a common understanding among scientists that propose a specific site. Because Taiwan LTSER is not a re-start or shift from the previous Long-term Ecological Research (LTER) in Taiwan, the potential conflict due to the lack of consensus on extending the research to include social dimension is avoided. Taiwan LTSER was initiated in 2021 and has established six sites by 2024. Based on the known challenges, Taiwan LTSER innovated the development and governance of LTSER to address the challenges. Thus, although it is still developing, sharing Taiwan LTSER experience to the academia is important and it would be informative to check the progress of Taiwan LTSER in the decades to come.

Motivation and conceptual background

The need of long-term social-ecological research

There is growing recognition that an integrated social-ecological system perspective is key to address the world's grand challenges concerning changes in the interlinked, and often entangled ecological and social systems (Fischer *et al* 2015, Van Dolah *et al* 2016, Currie *et al* 2024). Long-term social-ecological research (LTSER) is considered an ideal approach to provide transdisciplinary knowledge necessary for guiding actions toward sustainability transition (Bretagnolle *et al* 2018, Clara *et al* 2024). There are more than 50 LTSER platforms spreading over all continents by 2018 (Dick *et al* 2018). The LTSER platforms have major achievements including contributions to policies, land-use planning, and natural resource management (Holzer *et al* 2018a). Despite the global recognition and the achievements, there are major challenges in LTSER and two of the main challenges are rooted in the very essence of LTSER, 'long-term' and 'transdisciplinary' (Holzer *et al* 2019, Orenstein *et al* 2019).

Insights from LTER have illustrated that long-term studies are required for a rich understanding of ecosystems at multiple scales ranging from days to decades (Kratz *et al* 2003, Kuebbing *et al* 2018). Many gradual changes in system structure and function cannot be easily detected via short-term studies. For example, a one to three year study is unlikely to capture ecosystem changes caused by warming or atmospheric nitrogen deposition (Magill *et al* 1997, Pregitzer *et al* 2008, BassiriRad 2015) or empirically test how warming affects crop growth and income of farmers, although make predictions using models is possible (Kaiser *et al* 1993, Ojo and Baiyegunhi 2021). Similarly, short-term studies are unlikely to capture the whole picture of the perception of local residents on landfill as their perception may vary throughout the planning, installation and operation stages (Okeke and Armour 2000).

In addition to detecting gradual system changes, without long-term monitoring and surveys it is difficult to have baseline system conditions that can be used to evaluate the magnitude of system change caused by rare but extreme events. For example, a study of forest leaf area index (LAI) in northeastern Taiwan showed that there was an increasing trend of LAI between 1995 and 2010 from less than 1.5 to more than 4.0 (Chang *et al* 2020). The increasing trend may be interpreted as forest growth when in fact the forest was recovering from severe typhoon disturbance in the summer of 1994 (Lin *et al* 2011, Chang *et al* 2020). On the social system, the health risk and public opinion on nuclear power plants could be very different between regular periods and following accidental events such as the Fukushima Daiichii nuclear power plant accident (Aliyu *et al* 2015, Hasegawa *et al* 2015, Yamagata 2024). Thus, long-term research is necessary for detecting both gradual changes and rare but abrupt changes of systems. Changes in policy or governance can also have major effects on the systems. However, without multiple year monitoring, the social-ecological effects of changes in the physical environment or governance cannot be thoroughly understood. Given the increasing human intervention on social-ecological systems, long-term research becomes indispensable to evaluate the changes caused by human intervention and distinguish them from baseline variation or changes in the physical environment. In the justification of long-term studies in ecology, Franklin (1989) concluded that 'Long-term observations are central to almost every important ecological concept and to every environmental issue.' It is fair to extend the argument to emphasize the importance of long-term monitoring for every important social-ecological issue.

Transdisciplinary studies that involve both social and natural scientists as well as stakeholders are necessary because as described above most ecosystems are directly or indirectly affected by human activities. For example, the absence and re-appearance of wolves to the Yellowstone National Park both had tremendous impacts on biodiversity and ecosystem resilience and were both due to human intervention (Marshall *et al* 2013, Beschta and Ripple 2016) and the changes in the management policies were largely affected by rural culture and public concerns and interests (Nie 2001). The widespread of wind turbines which can impact bats and birds (Barclay *et al* 2007, Rydell *et al* 2010) arises from social demand of green energy and opposition to wind turbines are often from stakeholders affected by the installation and operation of wind turbines (Martínez-Mendoza *et al* 2020). Thus, it is not surprising that support for wind turbines is lowest among those living closest to the wind farm (Swofford and Slattery 2010). More importantly, the interactions between social system and ecological system are bidirectional (Guerrero *et al* 2018) such that a comprehensive understanding of changes in one system requires a thorough understanding of the other. For example, mangrove forests provide diverse ecosystem services, such as carbon sequestration, biodiversity provisioning, ecotourism, flood mitigation (Tri *et al* 1998, Menéndez *et al* 2020) but the expansion and shrinkage of the coastal mangroves is often more affected by human's perspective of their values to local communities than by changes in natural environmental conditions. This can be illustrated by the historical changes in the area of mangrove forests in the Philippines. Between 1950s and 1980, large area of mangroves were cut to make space for fish ponds and residential settlement, while since 1957 mangrove plantations started to expand due to first-come first-served ownership of trees to those who plant the trees (Walters 2003). All the examples described above point to the need of transdisciplinary research for sustainable management as we are 'in the Messy Entanglement of Complexity' (Rawluk *et al* 2020) in the Anthropocene.

Challenges of 'long-term' 'transdisciplinary' research

Long-term transdisciplinary research faces many challenges that cannot be effectively addressed through the efforts of researchers alone (i.e., a bottom-up approach) or solely through the initiatives of authorities or funding agencies (i.e., a top-down approach). This paper describes the dual challenges of sustaining long-term research and achieving transdisciplinarity. It further explores how a synergistic combination of bottom-up and top-down strategies can provide effective solutions to these challenges. Our definition of transdisciplinarity is based on the key characteristics of transdisciplinary research described by Holzer *et al* (2018b) in their evaluation of transdisciplinary research on coupled socio-ecological systems. It involves integrating knowledge from various disciplines and engaging stakeholders from different sectors, including academia, industry, government, and

civil society. The goal is to develop solutions that are not only scientifically sound but also socially relevant and practically applicable.

Although other challenges, such as maintaining consistent data collection and storage protocols, are significant, long-term funding support remains arguably the most critical challenge for long-term research. Without long-term funding, conducting and maintaining such research becomes exceedingly difficult, if not impossible.

Funding agencies typically do not support projects for more than five years. For example, the average duration of 2020 research grants awarded by the National Science Foundation (NSF) of the US was 2.8 years (NSF 2021), while the research period of Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science is 3–5 years (JSPS 2024). Shot-term funding may work for projects targeting at specific questions or testing particular hypotheses but is a main constrain for projects aiming to provide long-term holistic understanding of entangled social-ecological systems. Although many funding agencies have an evaluation system to decide the renewal of long-term studies, uncertainty exists which discourages scientists from making long-term commitments. A commentary to the Chilean LTSER network highlighted that without the political commitment from the state 'the LTSER system is subject to discontinuity and frequent interruptions, which jeopardizes the long-term effort to understand the functioning of nature and its biodiversity' (Frêne *et al* 2023). The worry about the uncertainty of long-term funding support can also be illustrated by the report from the Austrian Eisenwurzen LTSER platform which urged that 'consecutive research projects that have allowed for capacity building in the past may be threatened in the future if national Austrian research funders cease to provide resources' (Gingrich *et al* 2016). From the perspective of funding agencies, the challenge is the justification of long-term funding because different types of research are competing for the fixed amount of budget. However, this is a chicken-and-egg dilemma because without long-term support it is difficult to have long-term results to prove the importance and value of long-term research. Fortunately, studies have shown that long-term studies contribute disproportionately to ecology and policy (Hughes *et al* 2017, Bretagnolle *et al* 2018).

Many papers have discussed the challenges of transdisciplinary research (Lang *et al* 2012, Brandt *et al* 2013, Arpin *et al* 2023) and they pointed to several key factors. First, because the vast majority of scientists are trained in a specific field such that it takes extra efforts to conduct transdisciplinary research. For example, in an evaluation of the effectiveness of transdisciplinary social-ecological system research based on interviews of 66 stakeholders in the LTSER platform, Holzer *et al* (2019) concluded that 'although particular scientists at each platform have taken on entrepreneurial roles to operationalize transdisciplinary science a business-as-usual attitude tends to dominate institutions, limiting meaningful progress toward transdisciplinary objectives'. Fortunately, centers, departments and research institutes related to sustainability science, which emphasize transdisciplinary training, are emerging in recent years (Clark and Dickson 2003, Yarime *et al* 2012, Soini *et al* 2018). Second, many transdisciplinary research requires collaborations among people from different disciplines using different languages and methodologies and crossing the walls is by no means easy (Lang *et al* 2012, Siew *et al* 2016, von Wehrden *et al* 2019). Third, it generally takes longer to have good outcome from transdisciplinary research (partly due to the first and second factors) which does not fit the need for rapid publications for finding a job or securing tenure positions (Gleich 2016, Tian *et al* 2016). Fourth, current performance evaluation systems are mostly based on performance of domain science. Working on interdisciplinary or transdisciplinary research can be considered unfocused or even 'second rate' by scientists focusing on domain knowledge science (Eisenberg and Pellmar 2000, Arpin *et al* 2023). Bottom-up recognition of the importance of transdisciplinary research in addressing critical sustainability issues helps to motivate scientists to collaborate on transdisciplinary research and the outcome can be rewarding. However, based on the Taiwan experience we argue that changes in the way that funding agencies treat long-term research (i.e., a top-down approach) can facilitate the bottom-up movement of long-term transdisciplinary research.

For full disclosure, we noted that both authors play key roles in the establishment, operation and evaluation of Taiwan LTSER. TCL is running the Taiwan LTSER program office funded by National Science and Technology Council (NSTC) Taiwan and was also the coordinator of the Sustainability Program of NSTC in 2022-2024. He was also the coordinator of Taiwan LTER network and a member of the science committee of International LTER in 2007–2009. Thus, TCL is fully familiar with long-term research as well as transdisciplinary research, domestically and internationally. The mission of the LTSER program office is to assist the development of LTSER in Taiwan in close collaboration with each LTSER site to track/check if the development of the site is consistent with the project goals (see below). MTL was the deputy minister of NSTC Taiwan between 2021 and 2024. He is deeply devoted in linking knowledge to actions and set up important programs for sustainable development and just transition such as Taiwan LTSER and Taiwan Sustainability Hub. We believe that our engagement in the processes of Taiwan LTSER development as described in this paper allows us to share details and insights regarding the core value of Taiwan LTSER. Further, as described in Holzer and Orenstein (2023), self-reporting improves the transparency of what is often 'insider' process. Following

their logic, in this paper we attempted to be 'self-aware, introspective, and critical, when necessary,' (Holzer and Orenstein 2023) when reflecting upon the two major challenges we identified regarding LTSER establishment and operation.

The Taiwan experience in addressing the two challenges

From LTER to LTSER

Taiwan had the first research site of the Taiwan Ecological Research Network (TERN, Taiwan version of LTER) in 1993, funded by the LTER program of the National Science Council (now NSTC) (Hsia *et al* 2000). Taiwan Ecological Research Network together with three other member networks became the founders of the International LTER (ILTER) Network (Kim 2006). By 2000, seven LTER sites were in operation in Taiwan. However, the LTER program of NSC Taiwan was replaced by Biodiversity program in 2002. Despite this, a group of scientists are still conducting long-term ecological research on the sites and Taiwan remains an active member of ILTER.

Responding to a complaint regarding the cessation of Taiwan LTER program (during the 2020 Conference of R&D Directors of Colleges and Universities) and recognizing the entanglement between social systems and ecosystems, NSTC launched the LTSER program under the lead of the deputy minister of NSTC at that time, Dr Minn-Tsong Lin, to establish the LTSER network, that is different from the previous LTER network. The establishment of Taiwan LTSER is also different from the development of LTSER in Europe, in which 'Under the auspices of ALTER-Net [A Long-term Biodiversity and Ecosystem Research and Awareness Network], the European regional group of the global LTER network, LTER-Europe, was set up with a strong focus on LTSER.' (Mirtl *et al* 2013). In other words, LTSER platforms in Europe are largely a shift or a movement of existing LTER platforms from focusing mainly on ecological issues toward platforms that take into account of socioeconomic drivers on ecological changes. Learning from the reported challenges and constrains of LTSER as well as the voice of scientists involved in Taiwan LTER, Taiwan LTSER adopted an approach that combines top-down and bottom-up processes to address the two main challenges of LTSER, long-term funding and transdisciplinary research.

It is important to note that the complaint to the ceaseation of LTER was not a pure stochastic event. The frustration among ecologists regarding the cessation has been there for approximately two decades, with numerous discussions and growing pressures. In an informal opinion exchange time during the ceremony of a hub site of Taiwan Sustainability Hub in 2021, there was an in-depth discussion on the importance of evidence-based approach, which was highly supported by ecologists devoted to LTER. The discussion and the support of ecologists has triggered the deputy minister, who attended the meeting, to have the idea of starting a new program of LTSER rather than restarting LTER at NSTC. As a result, it was followed up by an intensive bottom-up professional engagement and scoping of ecologists together with scholars form extended disciplinaries as well as NGOs. This set up the first step for the establishment of LTSER in Taiwan at the time when most ecologists also recognized that social systems play a key role in characterizing ecosystem structure and function.

Treating LTSER platforms as a core facility to secure long-term funding

Recognizing that securing sustainable funding is one of the main challenges of long-term research aimed at assisting sustainable development, Dr Minn-Tsong Lin categorized Taiwan LTSER as a core facility of NSTC from the top-down to secure long-term funding. Core facility is not a new concept; many funding agencies around the world have core facilities that are under long-term funding support (Carter *et al* 2019, Kos-Braun *et al* 2020). For example, the National Oceanography Centre of UK, the National Science Foundation of the US, and NSTC of Taiwan provide long-term funding support for research vessels and vehicles, considering them as core facilities for marine research (Skinner *et al* 1987, Chang *et al* 2010, Konar *et al* 2017). These vessels function as research platforms serving scientists for various types of marine research. By treating LTSER sites as platforms supporting various studies at and around the sites, categorizing the LTSER platforms as a core facility is justified. The funding is allocated to support fundamental monitoring of biotic and abiotic environmental parameters (e.g., species composition and abundance, temperature, precipitation and substrate properties in the case of coastal ecosystems) as well as societal parameters (e.g., income and age structure of local communities). The monitoring of fundamental environmental and social parameters provides baseline and critical information that not only reflects the status and changes of the social-ecological system but also attracts scientists to conduct research at the sites. For example, with long-term monitoring of LAI, a surrogate of primary productivity, entomologists can explore how tropical cyclone disturbance alters insect community through its effect on LAI. With long-term monitoring of income of local community, social scientists can explore how changes in governance such as the ease of regulation on land use affect local community and ecologists can explore how it affects local biodiversity. Essentially, the LTSER sites are just like research vessels that function as platforms for

Table 1. Four criteria of Taiwan LTSER site selection.

1	The site should reflect characteristics of a certain type of social-ecological systems of Taiwan
2	The site should have existing or potential social demands that have major impact on the ecosystem and the ecosystem changes are likely to feedback to the society
3	The site must have rich social-ecological issues that would attract the engagement of researchers.
4	The operation team should be able to Leverage (external) resources to the site.

scientists to study the social and ecological systems and their interlinks at the sites. Thus, they are core facilities deserving long-term funding support.

Taiwan LTSER platforms were born with transdisciplinary concept

To ensure that transdisciplinary research is in the core of Taiwan LTSER sites, three of the four criteria for the selection of LTSER sites emphasize the transdisciplinary nature of the platforms (table 1). Initially, the principal Investigator (PI) of the Taiwan LTSER program office conducted an extensive literature review and from the review, it is clear that LTSER in the European LTER is the most active network with numerous success stories. To a large degree, the four criteria were derived from 'Long-Term Socio-Ecological Research Platforms: A best practice guide book' (Orenstein *et al* 2019).

Given the diverse nature of social-ecological systems, it is impractical to conduct LTSER across all systems. Thus, as an initial criterion, each proposed site must represent a specific type of social-ecological system in Taiwan. The goal is to use data from these representative platforms to enhance our understanding of similar systems. For instance, one of the first two platforms focuses on the Feitsui Reservoir in northern Taiwan, aiming to explore how mountain agriculture and land use policies affect water quality in reservoir catchments throughout Taiwan. Similarly, the Changhua platform in central Taiwan and the Southwest Coastal platform represent various coastal social-ecological systems in western Taiwan. Due to the interconnection between social and ecological systems, it is impossible to fully understand a system by studying only its social or ecological components. Thus, the second criterion mandates that proposals identify the interactions and entanglements between the social and ecological systems at the site. The budget for the LTSER core facility is allocated for long-term monitoring of key social-ecological systems rather than specific questions or hypotheses. However, a comprehensive understanding of social-ecological systems requires more than monitoring. Consequently, the third criterion also requires that scientists operating the platform identify social-ecological issues that can engage researchers. These researchers can apply for grants using the monitoring data to conduct studies at the site, thereby deepening our understanding of these systems. The fourth criterion encourages the operation team to seek additional funding sources to enrich the platform's monitoring and research activities. This approach not only broadens funding options but also engages more stakeholders. For example, the Southwest Coastal platform monitors fish diversity within the Tai-Chiang National Park, receiving supplementary funding from the park. The Hualien platform in eastern Taiwan secured funding from a solar power plant company to install and operate a flux tower.

By establishing these criteria in advance, the Taiwan LTSER platform ensures that proposed sites address interconnected social and ecological issues. In practice, each team that proposed a specific site was required to present the interactions and entanglements between social and ecological systems to convince the review committee, which consists of both social scientists and natural scientists. Using the Changhua site in central-west Taiwan as an example, the local team described how the coastal lagoon system is home to diverse fish and benthic animals, forming the foundation for the thriving aquaculture that is the most important traditional economic activity. The growth of mangrove plantations along parts of the coast for coastal protection increases the abundance of some animals but negatively impacts others. Additionally, the mangrove plantations not only reduce the area suitable for aquaculture but also alter the dynamics of the sediment, impacting the growth of aquaculture species and thus the local economy. Therefore, the local team listed biophysical and social monitoring and survey items that can illustrate and potentially quantify the interactions and entanglements. In other words, the program office did not set specific items for interactions and entanglements. Rather, it is up to the local team to persuade the review committee that the region hosts compelling socio-ecological policy dilemmas that could benefit from transdisciplinary research interventions over the long-term, that long-term observational data would provide needed support for such research, that the research team has a holistic understanding of the system, and that long term funding would be justified.

Our approach in developing Taiwan LTSER differs from most LTSER platforms in the ILTER network, which transformed from ecological to social-ecological research sites due to the motivation of certain key researchers but not all. Consequently, scientists working on these sites must overcome the challenges of transdisciplinary research to create a platform that integrates social and ecological disciplines. In contrast,

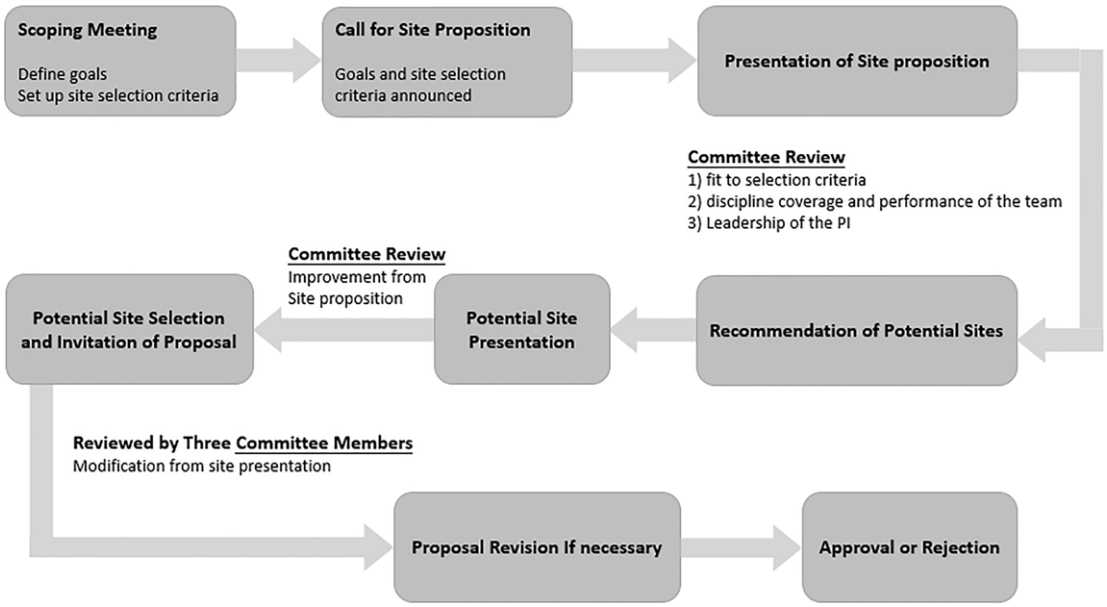

Figure 1. Taiwan LTSER platform establishment processes.

Taiwan LTSER sites are founded on transdisciplinary principles, fostering mutual understanding among the proposing scientists. While this does not guarantee seamless transdisciplinary research, it does mean that involved scientists are better prepared for such collaboration, reducing the likelihood of conflicts among them.

Our dual approach, which combines top-down and bottom-up processes, is not without challenges common to transdisciplinary research, such as reconciling differing priorities between policymakers and local stakeholders. Taiwan LTSER initiative is relatively new and remains in a 'learning by doing' process. However, scientists involved in Taiwan LTSER are keenly aware of these challenges, recognizing their importance in preparing site proposals and the subsequent operation.

Importantly, most platform operation teams are organized by scientists who have worked at these sites for many years prior to the platform's establishment. Consequently, they are familiar with both potential and actual conflicts between policymakers and local stakeholders, as well as among different groups of local stakeholders. For instance, in Changhua, central Taiwan, varying local perspectives exist regarding the installation of solar farms in the coastal area. The local team does not take a position on this issue; rather, they conduct *in situ* monitoring to assess the impact of solar farm installations and operation on local ecosystems and social economics.

With a core value of promoting sustainable development in Taiwan, Taiwan LTSER aspires to become a credible platform that provides empirical data on the changes and drivers of local socio-ecological systems. It is anticipated that the results of long-term monitoring will inform evidence-based policies and management programs, supporting sustainable and adaptive solutions.

Establishment, innovations, and challenges of Taiwan LTSER (figure 1)

In May 2021, NSTC funded the Taiwan LTSER platform program office. The program's PI has extensive experience with LTER, having coordinated Taiwan LTER in 2007 and 2008 and serving ILTER science committee during the period. The program office's mission is to establish LTSER platforms and ensure transdisciplinary research is central to their development. To achieve this, a bottom-up scoping meeting was held with 176 participants, including researchers and NGO representatives. Before the meeting, the PI drafted a call for platform establishment, outlining goals and selection criteria based on existing LTSER platforms, particularly in Europe, and Taiwan's unique social-ecological systems.

As described in the website under The Goal of Taiwan LTSER, 'The Taiwan LTSER platform seeks to identify socio-ecological systems that represent the diverse environments across the island'. However, as a relatively new and still developing network, Taiwan LTSER is still in the learning-by-doing process. Therefore, we intend to maintain flexibility regarding specific long-term goals and quantifiable indicators until we have a clearer understanding of what Taiwan LTSER can achieve as we expand to more sites across Taiwan. In addition, platform assessment is highly context-specific, both because it is place based, with unique interacting social and

Table 2. Location, type and key focus areas of Taiwan LTSER platforms.

Platform	Location	Representative systems	Key focus areas
Feitsui	Northern Taiwan	Reservoir Catchments	Water quality, social economics related to agriculture
Changhua	Central-West Taiwan	Coastal Social-Ecological Systems	Renewable energy (solar/wind farms), mangrove forests
Southwest Coast	South Taiwan	Coastal Social-Ecological Systems	Renewable energy, aquaculture
Lyudau	Small Island	Small Island Social-Ecological Systems	Tourism, traditional culture
Hualien	Eastern Taiwan	Eastern Plains and Basins	Tourism, forest plantations, solar farm development
Alishan	Indigenous Territory	Indigenous Social-Ecological Systems	Traditional hunting and plant collection practices

biophysical systems, and because they are managed in a bottom-up way where researchers appraise platform needs based on local context. Thus, it is imperative, from a network-wide perspective, to allow for flexibility in assessment criteria. However, we have listed long-term goals and quantifiable indicators, along with a common conceptual framework and standardized measurements/surveys, as top priorities to be discussed between the committee and the operations teams. With the general goal and the support of scientists familiar with the local social-ecological systems, we aim to establish a locally-driven LTSER network. We anticipate that the data gathered through long-term monitoring will encourage further research by scientists, enhancing the effectiveness of the LTSER core facility. Ultimately, we hope that the insights derived from these ongoing studies will inform sustainable governance practices and assist local communities in managing natural resources responsibly.

Additionally, in the context of global change, long-term monitoring will provide crucial baseline data to assess the impacts on and resilience of socio-ecological systems.' Thus, the data from long-term monitoring is expected to attract more scientists and support sustainable governance and resource use, while providing baseline information in the era of global change. Following this, a call for site proposals was made, and a presentation meeting took place. An evaluation committee recommended two potential sites, which were then approved by a panel of experts. The PIs of the selected sites submitted planning proposals, revised based on expert feedback. This process was repeated in subsequent years, leading to a total of six LTSER sites by 2024. Throughout, criteria for site selection were provided to ensure the quality of the platforms.

The six LTSER platforms in Taiwan cover diverse social-ecological systems, including reservoir catchments, coastal areas, small islands, eastern plains and basins, and indigenous territories (table 2). Each platform addresses specific environmental and socio-economic challenges, such as water quality, renewable energy, tourism, forest plantations, and traditional indigenous practices.

During site presentations and proposal reviews, site selection criteria were provided to ensure alignment with objectives. The fit of the proposal to the criteria, the discipline coverage and balance between social scientists and biophysical scientists as well as leadership of the PI were critically reviewed in the presentation of site proposition and site presentation stages. Each platform received an initial three-year funding term. About six months after establishment, the program PI and an expert visited the site to interact with the team and local stakeholders and check the quality of interactions between social and natural scientists.

At the end of each year, sites presented their progress to an evaluation committee who might expand funding if justified. Several months before the end of the first term, each platform presented their outcome and planned for the second term. Annual and end-term evaluations included site selection criteria to remind evaluators of Taiwan LTSER's goal of fostering a holistic understanding of social-ecological changes. In August 2024, the first two platforms passed the evaluation and received funding for the second term.

It is important to note that, through categorizing Taiwan LTSER as a core facility, long-term funding is secured for Taiwan LTSER. However, this does not mean that once a platform is established, it will receive continual funding regardless of its performance. Importantly, no platforms have failed the evaluation since the beginning of funding in 2021. However, the plan is that if a platform deviates from the scope of LTSER or if it does not continue to provide relevant research and data, it will be placed on probation for one year to improve before a final decision is made regarding its funding for the next phase. Following discussions among the members of the review committee, the criteria for evaluating the performance of the platforms include outputs and impacts. Outputs are quantifiable items such as the amount/types of data collected and deposited, the number of times data is downloaded, and the number of graduate students and postdoctoral researchers trained. Impacts include how the results from the platform are used to guide management and governance, as well as publications, theses, and research funding obtained based on data collected from the site.

Innovative approaches and persistent challenges

Taiwan LTSER employs innovative methods to secure long-term funding by defining LTSER platforms as a core facility through top-down changes and promoting transdisciplinary research by making it a key site selection criterion. However, several challenges persist, such as the need for rapid publications. Despite efforts to embed transdisciplinarity as a central component, issues related to divergent methodologies, stakeholder engagement, and knowledge co-production remain significant.

In addition to transdisciplinarity challenges, the core facility approach taken to securing long-term funding support may face new difficulties. Treating LTSER sites as platforms means that providing important baseline data, rather than studying specific socio-ecological issues, is the main objective of the platforms. Therefore, scientists devoted to maintaining the platforms may not have as many publishable outcomes as those working on question-oriented research projects. Given the importance of publications in the academic evaluation system, this could be a major concern for scientists involved in the platforms. Whether this can be overcome through collaboration between platform developers and question-oriented researchers, or by designing question-oriented studies and seeking other funding sources to support studies on the LTSER sites, remains to be seen.

Stakeholder engagement and case studies

Over the past three years, scientists have engaged with a broad range of stakeholders, from local community leaders and organizations to national policymakers. This collaboration has been particularly novel for many natural scientists, although Taiwan LTSER is still in its early stages, progress is evident, and platforms are actively addressing these challenges. The outcomes, while not yet fully realized, are promising.

Co-design, co-production, and co-delivery, although not explicitly included in the site selection criteria, are essential for effective transdisciplinary research and were emphasized during scoping meetings. Most sites have incorporated these elements into their monitoring processes, engaging diverse stakeholders.

For instance, at the Alishan platform, indigenous leaders facilitated collaboration by introducing scientists to their community and sharing local knowledge on historical agricultural practices and the distribution of regional flora and fauna. This collaboration was facilitated by the platform coordinator, who has been conducting research in the area, funded by the Forestry and Nature Conservation Agency. Indigenous leaders officially welcomed the LTSER team, enabling social scientists to conduct interviews. These interviews identified culturally significant plants critical for traditionally hunted mammals. This information was shared with plant scientists, leading to the inclusion of these plants in phenological monitoring. Indigenous communities also assisted in setting up camera traps in their hunting grounds and helped collect data.

The coordinator further engaged the Nature Conservation Agency, presenting the platform to secure permissions for using pre-existing camera trap data. While these connections predated the platform's establishment in March 2024, they have since strengthened, fostering deeper engagement between indigenous communities and scientists in co-design and co-production. Co-delivery has yet to be realized, but a consensus has been reached to share monitoring results collaboratively.

Sustainability and future directions

A potential challenge for the continued implementation of LTSER as a core facility by the funding agency (NSTC) lies in its novelty and non-traditional nature. While the inclusion of LTSER platforms in NSTC's core facilities is justified, this unconventional view may face resistance from institutions unfamiliar with the socio-ecological perspective. In societies where short-term returns on research and development investments are prioritized, and focus often remains on individual disciplines, the need for long-term transdisciplinary platforms addressing complex issues may be overlooked. Thus, achieving sustainable funding support for LTSER faces much greater challenges compared to other types of core facilities. While the top-down designation of LTSER platforms as core facilities has paved the way for long-term funding, ensuring its success requires sustained effort, especially during the first decade before the benefits of long-term monitoring become apparent.

The establishment of Taiwan LTSER was driven by a strong bottom-up call, and continued collaboration between the academic community and concerned NGOs is essential to ensure that key decision-makers within the funding agency recognize LTSER's potential to facilitate sustainability transitions. Highlighting that LTSER represents a shared interest of many scientists and NGOs will strengthen its position. These challenges can be addressed through effective networking among interdisciplinary communities and transforming aspirations into actionable outcomes, aligning with the Knowledge-to-Action (K2A) framework. Bottom-up consensus-building efforts, such as anticipatory governance initiatives, can play a vital role in securing support and fostering the sustainability of LTSER.

Despite its challenges, the ongoing construction of Taiwan LTSER is informed by known obstacles and incorporates innovative approaches to address them. While still in its formative stages, the experiences and

insights gained from building Taiwan LTSER and sharing them with the academic community can provide valuable lessons for similar initiatives globally. Furthermore, tracking the progress and outcomes of Taiwan LTSER in the coming decades will offer important perspectives on its long-term effectiveness and contributions to addressing socio-ecological challenges.

Taiwan LTSER as a model for countries experiencing rapid changes

Taiwan's rapid social-ecological changes provide a unique context for the development of Taiwan LTSER that can serve as a model for countries experiencing similar transformations. While social-ecological changes occur globally, the pace of change in Taiwan far exceeds that in Europe and North America. Taiwan's evolution from an agrarian society to a global technological leader has been both remarkable and rapid. Government-led reforms in land use, education, and industrialization during the 1960s and 1970s drove significant economic growth, transitioning Taiwan from traditional manufacturing to high-tech industries by the 1980s and 1990s. Recently, Taiwan has embraced sectors such as biotechnology, renewable energy, and artificial intelligence, supported by policies fostering a digital economy and smart cities. Taiwan's rapid development has made it highly dynamic, showcasing its resilience, adaptability, and ability to thrive in an ever-changing global landscape.

This rapid development of Taiwan mirrors trends in East and Southeast Asia, regions experiencing similar economic growth, urbanization, and associated environmental and social challenges (Iwami 2001). However, it has been argued that such rapid growth often does not align with pathways toward sustainable societies (Kim 2006). The dynamic nature of these regions underscores the importance of long-term monitoring to capture the drivers and indicators of system changes, as the outcomes of similar studies conducted at different times can vary significantly.

In Taiwan, net-zero policies, such as the large-scale deployment of wind turbines and solar farms along coastal plains and shorelines, have brought profound impacts on social-ecological systems over the past three years. Two of Taiwan's six LTSER platforms have entered their second term, providing valuable data to explore the effects of these policies on socio-ecological systems.

Compared to LTSER initiatives in Europe and North America, Taiwan's experiences offer lessons that may be more relevant and applicable to countries in East and Southeast Asia, where rapid environmental and socio-economic changes are intertwined with sustainability transitions.

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Data availability statement

No new data were created or analysed in this study.

Author contributions

T-CL led the manuscript, T-CL and M-TL contributed to the writing, conceptualization and editing and approved the final manuscript.

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Availability of data and material

Not applicable.

Code availability

Not applicable.

Declarations

Conflict of interest

For full disclosure, the authors have noted in the manuscript that both authors play key roles in the establishment, operation and evaluation of Taiwan LTSER. Teng-Chiu Lin is running the Taiwan LTSER program office funded by NSTC Taiwan and is also the coordinator of the Sustainability Program of NSTC. He was also the coordinator of Taiwan LTER network and a member of the science committee of ILTER in 2007-2009. MTL was the deputy minister of NSTC Taiwan between 2021 and 2024. He is deeply devoted in linking knowledge to actions and set up important programs for sustainable development and just transition such as the including Taiwan LTSER and Taiwan Sustainability Hub. We believe that our engagement in the processes of Taiwan LTSER development as described in this paper allows us to share details and insights regarding the core value of Taiwan LTSER.

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