

Review

Empowering Citizens Through Co-Learning: A Conceptual and Methodological Framework for Transitions Toward Sustainable and Resilient Communities [†]

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Abstract

Environmental challenges, such as climate change, resource circulation, and biodiversity loss, are closely interrelated with regional issues, including population decline, aging, youth outmigration, and the maintenance of local industries. Addressing these challenges requires not only scientific and technological innovation but also educational and participatory approaches that empower citizens to engage with complex regional issues. This paper conceptualizes co-learning as a framework for environmental education and citizen engagement in transitions toward sustainable and resilient communities. Co-learning is defined as a multi-actor learning process in which participants with diverse forms of knowledge and social positions revise their understandings, relationships, and orientations toward action through dialogic and reflective interaction. The paper organizes co-learning into a conceptual and methodological framework that connects environmental education, citizen engagement, science communication, technology assessment, community-based projects, and policy-oriented learning. It proposes four types of co-learning—interdisciplinary, bridging, project-based, and policy co-learning—and identifies design principles and analytical dimensions for examining learning outcomes and empowerment processes. Illustrative practices in Tanegashima, Japan, help clarify how the proposed framework can connect science, education, and citizen engagement.

Keywords: co-learning; environmental education; citizen engagement; science communication; regional sustainability transitions; agency formation

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1. Introduction

Contemporary environmental challenges, such as climate change, resource circulation, biodiversity loss, and pollution, cannot be addressed by scientific and technological innovation alone. These challenges are closely bound up with local economic structures, demographic changes, lifestyles, education, cultural values, and policy-making. In rural,

island, and other nonmetropolitan regions, population decline, aging, youth outmigration, shrinking local industries, and the weakening of local capacities for collective action all affect environmental issues and the ways they can be addressed. Research on sustainability transitions has therefore emphasized that sustainability challenges require long-term societal transformations, including changes in institutions, technologies, economies, culture, and everyday practices [1–4]. In transitions toward sustainable and resilient communities, it is not sufficient for experts to provide scientific knowledge or technological solutions alone. Instead, citizens, local governments, businesses, schools, students, and researchers need opportunities to understand regional challenges in relation to their lives and futures and to learn, deliberate, and act together by exchanging knowledge, experiences, values, and concerns.

Environmental education and education for sustainable development (ESD) have long sought to cultivate the knowledge, attitudes, skills, and values that are necessary for sustainable action. More recently, attention has shifted away from one-way knowledge transmission toward experiential, collaborative, and locally grounded approaches to learning, including place-based education, service learning, community-based learning, active learning, and citizen science. Place-based education emphasizes the use of local nature, culture, history, industries, and social issues as resources for learning, connecting learners to the places where they live [5]. Critical pedagogy of place argues that place-based learning should not only foster attachment to place but also enable learners to critically examine environmental degradation, social inequality, and the political dimensions of local issues [6]. For their part, service learning and community-based learning connect educational activities with civic responsibility, community engagement, and practical problem-solving [7,8].

Locally grounded environmental education is particularly relevant in regions that are facing demographic decline and youth outmigration. For young people in rural and island regions, the relationships among career formation, place attachment, and future engagement with their home communities are critical issues in regional sustainability. Previous studies have indicated that place attachment, sense of community, and locally embedded learning can influence young people's perceptions of their future relationship with their own home regions [9–11]. Longitudinal ESD studies also suggest that sustainability-related knowledge, values, attitudes, and orientations to action develop over time rather than through one-off interventions [12]. School-based sustainability education in Japanese island regions has also found that continuous, locally grounded curricula have the potential to foster young people's understanding of regional sustainability and their awareness of community engagement [13].

However, the learning required for transitions toward sustainable and resilient communities is not limited to formal education or youth development. Regional decarbonization, the deployment of renewable energy, sustainable mobility, resource circulation, and sustainable agriculture and forestry require scientific knowledge and the development of technology, but they are also closely related to residents' everyday lives, experiences, values, concerns, and expectations. Science communication research has repeatedly criticized the deficit model, which assumes that public understanding and acceptance can be achieved by filling the gaps in citizens' knowledge through expert explanation [14–17]. In contrast, public engagement with science emphasizes dialogue, participation, and deliberation as means of connecting scientific knowledge with public values, local experience, and issues of social concern [18–20].

Nevertheless, the simple creation of opportunities for dialogue or participation will not automatically produce equitable or transformative learning [21,22]. Experts and non-experts differ in their knowledge, institutional authority, communicative power, and social position. In addition, citizens' questions, concerns, disagreement, and dissatisfaction

should not be treated as simple barriers to social implementation or as negative factors that need to be overcome. Instead, they reveal conflicting values, everyday constraints, uncertainties that are associated with technological change, and problem framings that could remain invisible in relation to expert-led research and policy processes [23,24]. Thus, environmental education and science communication should not only be understood as processes for improving citizens' understanding of science and technology; they can also be understood as processes through which experts, researchers, and institutions reconsider their assumptions, research agendas, and technological options in light of locally situated knowledge and concerns.

This perspective also resonates with sustainability science and transdisciplinary research, which emphasize co-design and co-production by researchers and societal actors [25], the integration of scientific and practical knowledge [26,27], and collaborative knowledge processes in participatory settings [28–30]. In this paper, however, the key issue is not only collaborative knowledge production but also how diverse actors learn from one another, how relationships change, and how orientations toward action are transformed through interaction. This highlights the need to conceptualize co-learning more explicitly as a learning-oriented framework for regional sustainability transitions.

The term co-learning is used in educational contexts to describe relationships in which teachers, students, and other learners learn together, as well as in sustainability transition studies, in which learning is emphasized across various transition narratives and between researchers, experts, and regional stakeholders [31–33]. Related discussion of social learning in environmental management and sustainability science has likewise emphasized collective learning across several actors, while indicating the need for clearer conceptual and analytical grounding [34–36]. However, these uses remain dispersed across educational practice, transition theory, technology assessment, and participatory research. This dispersion is not merely a terminological issue. Within regional sustainability practices, activities such as technology assessment, expert–resident dialogue, environmental education, youth capacity building, community visioning, and policy formation often coexist, influencing one another. Yet, without a clearer conceptualization of co-learning, these practices often remain fragmented, and their cumulative contribution to transitions in regional sustainability is difficult to understand.

The need for a framework to encompass these considerations is also grounded in practice. Kikuchi et al. [33] showed how technology assessment for biomass energy systems in Tanegashima could be connected with stakeholder learning and regional transformation. However, transitions in regional sustainability involve more than the assessment and contextualization of specific technologies; they also involve educational processes, citizen engagement, youth development, community-based projects, and institutional or policy-oriented learning. The main practical challenge is therefore to understand how these diverse activities can be designed, connected, and evaluated as related forms of co-learning.

This paper does not claim that the term “co-learning” itself is new. Rather, the original contribution of this paper lies in systematizing co-learning as a conceptual and methodological framework for regional sustainability transitions. Specifically, this paper makes three contributions. First, it connects discussions that have often been treated separately, including environmental education, citizen engagement, science communication, technology assessment, community-based projects, and policy-oriented learning. Second, it proposes a typology of co-learning—interdisciplinary, bridging, project-based, and policy co-learning—to clarify different actor relationships, knowledge interfaces, and purposes. Third, it identifies design principles and analytical dimensions that can be used to design, compare, and analyze co-learning practices in regional contexts.

In this paper, co-learning is defined as a multi-actor learning process in which participants with diverse forms of knowledge and social positions revise their understandings, relationships, and orientations toward action through dialogic and reflective interaction. This definition emphasizes that co-learning is neither one-way knowledge transfer nor merely two-way communication or consensus building. Instead, it is a process through which problems are reframed, knowledge is contextualized, relationships are built, and agency for action is fostered in transitions toward sustainable and resilient communities.

2. Conceptual Foundations of Co-Learning

This section reviews the conceptual foundations of co-learning in relation to science communication, transdisciplinary research, knowledge co-production, and environmental education. Co-learning is not understood here merely as a joint learning activity among several people. Rather, as the following sections show, it is a multi-actor process through which different forms of knowledge and experience are connected, contextualized, and oriented toward action in regional sustainability transitions.

2.1. Existing Approaches and Remaining Gaps

2.1.1. From Knowledge Transfer to Participatory Engagement

Early models of science communication and environmental education tended to emphasize the transmission of scientific knowledge from the expert to the citizen. This approach, which is commonly referred to as the deficit model, interprets public concerns, skepticism, and opposition to science and technology as mainly resulting from insufficient knowledge or misunderstanding. However, the public response to science, technology, and environmental questions cannot be explained by a simple lack of information. As Wynne [14] and Irwin [15] have shown, citizens tend to interpret science and technology through their lived experience, local knowledge, value judgments, and relationships of trust. Understanding public responses as merely knowledge deficits therefore cannot capture the complex relationships among science, technology, and society.

In response to critiques of the deficit model, science communication has increasingly emphasized dialogue, public participation, and public engagement. Rowe and Frewer [18] distinguished a range of forms of public engagement, including the provision of information, consultation, and participatory decision-making. Chilvers [19] highlighted the important role of learning and reflexivity in public dialogue on science and technology. Likewise, the framework of responsible innovation that was proposed by Stilgoe et al. [20] emphasizes anticipation, reflexivity, inclusion, and responsiveness in both the development and implementation of science and technology.

These discussions have modified science communication, guiding it away from one-way knowledge transmission and toward participatory and dialogic engagement. However, the simple creation of opportunities for dialogue or participation does not automatically lead to mutual learning or to relational change [21]. Experts and citizens tend to differ in their knowledge, institutional authority, communicative power, and social position. Moreover, citizens' queries, concerns, disagreements, and dissatisfaction should not be treated as simply negative factors that can hinder social implementation; they can instead serve as important knowledge resources for reconsidering the assumptions that underlie science, technology, and policy [24]. Therefore, if participatory engagement is to be further developed, it is necessary to examine not only whether participation occurs, but also what kinds of learning, reflection, and relational change can emerge through participation.

2.1.2. Knowledge Co-Production and Transdisciplinary Research

Both sustainability science and transdisciplinary research recognize that expert knowledge alone is not sufficient for addressing complex societal challenges. Issues such as climate change, decarbonization, resource circulation, biodiversity loss, and regional decline require the application of knowledge from the fields of the natural sciences, engineering, the social sciences, and the humanities. In addition, they also require the practical and experiential knowledge of residents, local governments, businesses, nonprofit organizations, and educational institutions. For this reason, co-design and co-production, in which researchers and societal actors jointly engage in problem framing, knowledge production, and solution development, are central to sustainability research [25].

Lang et al. [26] reported that transdisciplinary sustainability research is an approach integrating scientific and practical knowledge to address socially relevant problems. Jahn et al. [27] similarly positioned transdisciplinarity as not only involving integration across academic disciplines but also requiring the integration of knowledge between science and society. Mauser et al. [28] identified the importance of knowledge co-creation in global change research to pursue sustainability. In addition, studies involving living labs and participatory action research have highlighted the production of knowledge through collaboration among diverse actors in real-world settings [29,30].

These approaches make important contributions, connecting expert knowledge and societal knowledge, research and practice, and the production of knowledge and action. Recent work has also clarified the principles, modes, and impact mechanisms of knowledge co-production in sustainability research [37–39]. In addition, learning within transdisciplinary co-production has begun to receive increasing attention [40]. Building on these studies, the present paper focuses more specifically on how participants revise their understandings, relationships, and orientations toward action through interaction.

In other words, co-production is a useful approach to understanding the joint production of knowledge and outputs, although an additional perspective is required to explain the learning and relational transformation that take place within such processes. In regional sustainability transitions, it is important to do more than produce knowledge together; developing an understanding of how researchers, citizens, local governments, businesses, and educational institutions revise problem framings and action possibilities through engagement with one another's knowledge and values is also necessary.

2.1.3. Learning-Based Approaches in Environmental Education

Environmental education and ESD have developed a range of approaches for enabling learners to understand environmental issues and connect such understanding to sustainable action. Place-based education includes the incorporation of local nature, history, culture, industries, and social issues as learning resources, allowing learners to connect educational content with their own lived environments [5]. Gruenewald's [6] critical pedagogy of place argues that place-based learning should go beyond cultivating attachment to place by encouraging learners to critically examine inequality, environmental degradation, and power relations that are embedded in place. Service learning and community-based learning also connect learning with community participation, civic responsibility, and practical problem-solving [7,8].

Citizen science has also developed as a practice in which citizens participate in scientific knowledge production through observation, data collection, and analysis [41,42]. Citizen science can contribute to the accumulation of scientific data and to the participants' own environmental literacy, scientific understanding, environmental awareness, and behavioral intentions [43]. With respect to the theme of empowering citizens through science, citizen science and participatory environmental education are important aspects, as they position citizens as more than passive recipients of knowledge but as actors who

can engage with environmental issues. Recent school-based citizen science research has further indicated that co-creation among students, teachers, and researchers can support sustainability education by connecting scientific inquiry with curriculum-based learning, collaboration, and real-world socio-ecological issues [44].

These learning-based approaches provide important perspectives for understanding environmental education, not merely as knowledge acquisition, but as a type of learning that emerges through relationships with place, experience, others, and practice [45–47]. Sustainability learning also forms a process in which learners can connect environmental issues to their own lives and to their own future participation in society [46].

Meanwhile, environmental education, place-based education, service learning, and citizen science focus on specific domains of practice, such as formal education, community-based education, or citizen participation in scientific activities. A broader framework is therefore required to understand processes in which multiple actors, including experts, citizens, local governments, businesses, schools, and local communities, can learn from one another about science, technology, regional issues, policy formation, and social implementation.

Science communication, knowledge co-production, transdisciplinary research, and environmental education collectively demonstrate the importance of participation, dialogue, collaboration, and practice-based learning that goes beyond one-way knowledge transmission. However, these approaches have been developed in different domains of practice, and there remains a need for a cross-cutting conceptual framework that explains how diverse actors revise their understandings, relationships, and orientations toward action through interaction. The following section turns to co-learning as a concept that can respond to this gap.

2.2. Conceptualizing Co-Learning for Sustainable and Resilient Communities

Building on the limitations of the existing approaches reviewed above, a cross-cutting conceptual framework is needed to connect environmental education, citizen engagement, science communication, technological contextualization, regional capacity building, and policy formation while focusing on mutual learning and transformation across multiple actors. This section examines the existing uses of co-learning and presents the definition that is used in this paper, followed by a clarification of its relationship with related concepts.

2.2.1. Existing Uses of Co-Learning

The term co-learning is used in several contexts. First, in educational research, it can describe relationships in which teachers and students, teacher educators and teachers, researchers and teachers, or learners themselves can learn together. For example, Jaworski [31] discussed the creation of co-learning partnerships in mathematics education and teacher education, in which teachers, teacher educators, and researchers jointly engage in professional development and in improving their teaching practice. Thus, co-learning challenges the assumption that knowledge is simply transmitted from those who know to those who do not, and instead emphasizes reciprocal learning among actors involved in education.

Second, in sustainability transition studies, co-learning is used to describe learning across a range of transition narratives. Luederitz et al. [32] argued that a multiplicity of sustainability transition narratives should not be understood merely as competing pathways but as having various intervention points and roles. Their work emphasizes the importance of learning across different visions, problem framings, and transformation strategies instead of relying on a single transition narrative.

Third, co-learning is also used in the context of regional technology implementation and technology assessment. In a case study of biomass energy systems in Tanegashima, Japan, Kikuchi et al. [33] incorporated technology assessment, including life cycle assessment, input–output analysis, and choice experiments, into co-learning. Their study is important because it showed that technical assessment can be embedded in stakeholder learning and in regional transformation rather than remaining within expert-led evaluation.

These uses are all important, although they remain dispersed across educational practice, transition narratives, technology assessment, and participatory research. The following subsection presents a definition of co-learning that is adopted in this paper.

2.2.2. Defining Co-Learning for Sustainable and Resilient Communities

Based on the preceding discussion, this paper defines co-learning in the following way:

Co-learning is a multi-actor learning process for regional sustainability transitions in which participants with diverse forms of knowledge and social positions iteratively revise their understandings, relationships, and orientations toward action through dialogic and reflective interaction.

The key point here is that co-learning is neither a simple one-way knowledge transfer nor merely a case of two-way communication. Co-learning is not reducible to a process in which experts explain scientific knowledge to citizens and citizens then come to understand it. Nor is the mere existence of communication between experts and citizens sufficient. If co-learning is to occur, interaction must produce a revision of participants' understandings, relationships, orientations toward action, or some combination of these.

Co-learning is also not simply a method of increasing public acceptance of technologies or policies that are predefined by experts or policy-makers. Citizens' questions, concerns, disagreement, dissatisfaction, and knowledge that are based on their lived experience should be treated as resources for the reframing of problems and for the contextualization of technologies and policies. Thus, co-learning is a process of mutual transformation in which all participants, including experts, encounter one another's knowledge, values, concerns, and future visions, and thereby revise the ways in which they understand problems, relate to others, and imagine possible actions.

2.2.3. Relationship with Related Concepts

Co-learning is closely related to several existing concepts, but it is not identical to these. Table 1 summarizes the relationship between co-learning and related concepts.

Table 1. Conceptual positioning of co-learning in relation to existing approaches.

Related Concept	Main Focus	Relationship with Co-Learning
Knowledge transfer	Transmission of knowledge from experts to citizens	Co-learning emphasizes mutual revision of understanding rather than one-way transmission.
Science communication	Sharing, explaining, and discussing scientific knowledge	Co-learning includes not only scientific understanding but also changes in relationships and orientations toward action.
Public engagement	Citizen participation, dialogue, and deliberation	Co-learning focuses not simply on whether participation occurs, but on mutual learning and transformation through participation.
Citizen science	Citizen participation in observation, data collection, and analysis	Co-learning can include citizen participation in science, but more broadly addresses multi-actor learning and problem reframing.

Co-production	Joint production of knowledge or outputs	Co-learning focuses not only on outputs, but also on the revision of participants' understandings, relationships, and action possibilities.
Transdisciplinary research	Collaboration between academic disciplines and societal practice	Co-learning explicitly captures learning, relational change, and action orientation within such collaboration.
Project-based learning (PBL)/Community-based learning (CBL)	Learning through practice and regional or community issues	Co-learning includes educational practices but extends to mutual learning among citizens, experts, governments, and businesses beyond schools.
Deliberation	Reason-giving discussion and public judgment	Co-learning regards deliberation as one possible condition, while focusing on learning and mutual transformation through dialogue.

As this comparison shows, co-learning cannot replace existing concepts. Rather, it reconnects the issues that they have addressed—knowledge, participation, dialogue, collaboration, and practice—from the perspective of learning and transformation. The distinctiveness of co-learning is found in its focus not only on what diverse actors produce through interaction but also on how participants' understandings, relationships, and action possibilities are revised through that interaction.

Accordingly, this paper positions co-learning as a multi-actor process of learning that supports knowledge integration, contextualization, relational change, and agency formation in the context of regional sustainability transitions. The following section develops a typology for understanding co-learning in relation to different forms of practice and actor relationships.

3. Typology and Design Principles of Co-Learning

3.1. Typology of Co-Learning

Co-learning is not a single activity format; it can take different forms depending on who participates, what kinds of knowledge and experience are connected, and what kinds of changes are expected or intended. To understand co-learning practices in regional sustainability transitions, this paper classifies co-learning into four types: interdisciplinary co-learning, bridging co-learning, project-based co-learning, and policy co-learning (Table 2).

This typology is not intended to provide a rigid classification of practices. In actual regional settings, multiple types of co-learning can overlap. For example, interdisciplinary collaboration among researchers can provide a basis for bridging co-learning between experts and local stakeholders. Similarly, agency that is formed through project-based co-learning could later develop into policy co-learning. The typology should therefore be understood as an analytical framework for the design and examination of co-learning practices.

Table 2. Typology of co-learning for sustainable and resilient communities.

Type	Main Participants	Knowledge and Experience Connected	Main Objective
Interdisciplinary co-learning	Researchers and engineers from different fields	Scientific, technical, and methodological knowledge across disciplines	Integrating expert knowledge and forming shared problem framings for complex regional issues
Bridging co-learning	Researchers, engineers, citizens, local residents, businesses, and local governments	Expert knowledge, local knowledge, lived experience, concerns, and values	Connecting expert and local knowledge and recontextualizing science, technology, and policy in local settings

Project-based co-learning	Students, citizens, community groups, businesses, educators, and researchers	Educational knowledge, local issues, practical experience, and future visions	Fostering agency and capacity through concrete regional projects
Policy co-learning	Local governments, residents, researchers, businesses, and civic organizations	Institutional knowledge, policy knowledge, lived experience, and public values	Reframing policy issues and options through mutual learning and incorporating local knowledge into institutional processes

3.1.1. Interdisciplinary Co-Learning

Interdisciplinary co-learning is a process in which researchers and engineers with expertise in different fields learn from one another to address complex regional issues. Challenges such as climate change, resource circulation, energy transitions, regional mobility, and sustainable agriculture and forestry cannot be addressed by a single academic or technical field alone. Instead, they require an integration of a range of knowledge rooted in the natural sciences, engineering, the social sciences, the humanities, policy studies, and education research.

Transdisciplinary research and sustainability science emphasize the importance of knowledge integration across disciplines in the ways in which complex societal problems can be addressed [26,27]. Interdisciplinary co-learning can provide a basis for this integration by enabling researchers and engineers to understand one another's concepts, methods, assessment criteria, and underlying assumptions and to develop shared problem framings.

3.1.2. Bridging Co-Learning

Bridging co-learning is a learning process connecting expert knowledge with locally situated knowledge among researchers, engineers, citizens, local residents, businesses, and local governments. This is particularly important for issues such as renewable energy development, resource circulation, mobility transitions, and the use of local resources, in which scientific and technical knowledge is necessary but also deeply intertwined with residents' everyday lives, values, and concerns.

Studies of science communication and public engagement show that the one-way provision of information from experts to citizens is not sufficient for addressing the relationship between science, technology, and society [14,15,18]. Building on this perspective, bridging co-learning is not a method that can be used to increase public acceptance of predefined technologies or policies. Instead, it is a process in which expert knowledge and local knowledge mutually question and reinterpret each other, enabling problem framings and possible solutions to be reconsidered in light of local contexts.

3.1.3. Project-Based Co-Learning

Project-based co-learning is a process in which citizens, students, community groups, businesses, local governments, educators, and researchers learn from one another in concrete projects and practical activities that address regional issues. This is closely related to environmental education, ESD, place-based education, project-based learning, community-based learning, and service learning.

Place-based education incorporates local nature, history, culture, industries, and social issues in the form of learning resources, deepening the relationship between learners and the places where they live [5]. Service learning and community-based learning can connect education with community participation and practical problem-solving [7,8]. Project-based co-learning builds on these educational approaches, emphasizing that learners

can develop as actors who engage with regional sustainability challenges through collaboration with others.

3.1.4. Policy Co-Learning

Policy co-learning refers to a process in which local governments, residents, researchers, businesses, and civic organizations can learn from one another in relation to policy formation and institutional design. Regional sustainability transitions require more than individual technologies or educational practices; they also require changes in public policy, planning, resource allocation, and governance. For this reason, policy processes must incorporate residents' lived experience and local knowledge while also making institutional and technical knowledge accessible to them.

Studies of public participation and deliberative democracy emphasize the importance of incorporating a range of citizen perspectives and values in policy-making [48,49]. Policy co-learning goes beyond any consultation or opinion gathering, involving mutual learning among residents, policy-makers, and experts with respect to policy problems, feasibility, institutional constraints, and local impacts. Policy co-learning can also emerge when understandings and relationships formed through bridging or project-based co-learning are connected to institutional or policy processes.

3.2. Design Principles for Enabling Co-Learning

Although the four types of co-learning differ in their participants, knowledge relationships, and primary objectives, they share several design principles. Table 3 summarizes the key principles for enabling co-learning.

Table 3. Design principles for enabling co-learning.

Design Principle	Rationale	Key Considerations
Ensuring diversity and heterogeneity	Mutual learning emerges through encounters among different forms of knowledge, values, experiences, and social positions	Participant composition; diversity of age, occupation, expertise, and local experience; inclusion of less visible voices
Dialogic fairness	Asymmetries in knowledge, authority, and communicative power may distort dialogue	Opportunities to speak; access to information; handling of technical terminology; framing of questions
Combining individual reflection and group dialogue	Learning requires both interaction with others and reflection on one's own assumptions and values	Individual work; small-group dialogue; peer-nary sharing; reflection before and after dialogue
Translation and contextualization of knowledge	Expert knowledge and local knowledge are not automatically understandable or usable across contexts	Visualization; translation; connection to local context; incorporation of lived experience into research and policy
Facilitation and mediation	Mutual learning does not occur simply by gathering diverse actors	Process design; handling disagreement; support for participation; knowledge brokerage; role of coordinators
Continuity and feedback	Co-learning is an iterative process rather than a one-off event	Continued learning opportunities; feedback of results; connection to subsequent practice; longitudinal evaluation

3.2.1. Ensuring Diversity and Heterogeneity

Co-learning requires encounters among various forms of knowledge, values, experiences, and social positions. Ensuring diversity and heterogeneity among participants is therefore a fundamental design principle. Research on public engagement and deliberation shows that the composition of participants and the quality of the participation influence the quality of public dialogue and decision-making [18,48,50,51]. Transdisciplinary

research similarly emphasizes the importance of involving actors from different academic fields and social positions in understanding complex societal problems [26,27].

However, diversity does not function automatically simply because diverse participants are present. It is necessary that different perspectives be expressed, listened to, and made meaningful. In co-learning, diversity and heterogeneity are not simply participant attributes; they are conditions that enable mutual learning and problem reframing.

3.2.2. Dialogic Fairness

Dialogic fairness is essential for enabling co-learning. Experts, citizens, local governments, businesses, and students may differ in knowledge, institutional authority, communicative power, and social position. The creation of a dialogue space does not by itself eliminate these asymmetries.

The study of deliberative democracy and public engagement emphasizes conditions under which participants can give reasons, listen to others, and reflect on their own views [19,49,51,52]. In co-learning, dialogic fairness does not mean that all participants must reach the same conclusion. Rather, it requires conditions under which different forms of knowledge and values are treated seriously, participants can express their views, encounter the perspectives of others, and reconsider their own assumptions.

3.2.3. Combining Individual Reflection and Group Dialogue

Co-learning requires not only dialogue with others, but also opportunities for participants to reflect on their own assumptions and values. Theories of experiential and transformative learning show that learning does not occur merely through experience, but also through reflection on experience and the transformation of meaning perspectives [53–55]. In both service learning and community-based learning, reflection is essential for the transformation of community experience into learning [7].

In co-learning settings, it is useful to combine individual reflection, small-group dialogue, and plenary sharing. These staged processes can reduce inequalities in speaking opportunities, allowing participants to clarify their views before engaging with others.

3.2.4. Translation and Contextualization of Knowledge

Co-learning requires the translation of expert knowledge into local contexts, as well as the connection of local knowledge and lived experience to the language of research and policy. Expert knowledge might not be readily understandable to local actors when it is presented in technical terms. Conversely, residents' experiences and concerns may not be easily incorporated into research agendas or policy design without appropriate mediation.

Here, transdisciplinary research emphasizes the importance of the mediation and integration of scientific and practical knowledge [26,27]. The concept of socially robust knowledge likewise highlights that knowledge should be more than scientifically valid, needing to be socially trusted and contextually relevant as well [56]. For co-learning, translation and contextualization are more than mere matters of simplifying expert knowledge. They include processes in which expert knowledge and local knowledge are mutually reinterpreted.

3.2.5. Facilitation and Mediation

Facilitation and mediation are necessary for connecting different forms of knowledge, social positions, and values. Merely bringing diverse actors together cannot guarantee meaningful dialogue. Expert voices may dominate, only a limited number of participants may speak, or disagreement may be avoided in favor of superficial consensus.

The study of public engagement and participatory research emphasizes the role of design, facilitation, and mediation in supporting participation processes [18,19]. Studies of living labs and co-creation likewise highlight the importance of intermediaries and process design to connect diverse actors and enable collaborative practice [29,30]. In co-learning, facilitation includes creating opportunities to speak, translating between expert and local knowledge, handling disagreement and concerns, and encouraging reflection.

3.2.6. Continuity and Feedback

Co-learning should be understood as an iterative process of interaction, practice, reflection, and redesign rather than as a one-off event. Transitions in regional sustainability are long-term processes, and single workshops or lessons are unlikely to generate sufficient relational change or agency formation.

Transdisciplinary research emphasizes iterative processes of problem framing, knowledge production, implementation, and evaluation [26,27]. Participatory action research likewise emphasizes iterative cycles of action, reflection, and learning performed by researchers and participants [55,57]. ESD and environmental education research suggest that sustainability-related knowledge, attitudes, and action orientations develop through continued learning experiences rather than through short-term interventions alone [12]. To embed co-learning in regional contexts, it is necessary to provide continued learning opportunities, feedback of results to participants, and connections to subsequent practices.

These design principles are applicable across all four types of co-learning, although their relative importance differs by type. In particular, interdisciplinary co-learning requires translation in disciplinary concepts and methods. Bridging co-learning emphasizes translation between expert and local knowledge, mutual trust, and dialogic fairness. Project-based co-learning significantly depends on agency formation through practice and continuity. Policy co-learning requires articulating values and interests and reframing policy options under institutional constraints. The typology and design principles provide a basis for designing co-learning practices, but an analytical perspective is also needed to examine what kinds of outcomes such practices produce.

4. Analytical Framework for Co-Learning Outcomes

The outcomes of co-learning cannot be sufficiently captured by asking only whether knowledge was transmitted, whether participants were satisfied, or whether consensus was reached. Through co-learning, actors with different forms of knowledge and social positions can revise their understandings, relationships, and orientations toward action through interaction. Its outcomes must therefore be understood across multiple dimensions, including knowledge, context, relationships, and agency. While these dimensions can be analytically distinguished, they often overlap in practice; knowledge integration may support contextualization, relational change, and agency formation.

4.1. Expected Outcomes of Co-Learning

4.1.1. Knowledge Integration

The first expected outcome is knowledge integration. In co-learning, various actors bring together their knowledge, experience, values, and perceptions of problems, which then become connected through dialogue and practice. The integration of knowledge does not mean simply adding expert knowledge to local knowledge, scientific knowledge to lived experience, or institutional knowledge to citizens' values. Rather, it means that these forms of knowledge are mutually interpreted; in this way, the understanding of problems and possible solutions can become revised.

Knowledge integration is central to transdisciplinary research and knowledge co-production [25–28]. Co-learning builds on these discussions, but it focuses specifically on the ways in which participants revise their own understandings through engagement with others' knowledge. In interdisciplinary co-learning, this may appear as integration across disciplinary concepts, methods, data, and assessment criteria. In bridging co-learning, this may appear as a connection between expert knowledge and local knowledge. In project-based co-learning, it may appear as a connection between school-based learning and regional realities. In policy co-learning, it may appear as the connection between institutional knowledge, administrative information, residents' lived experience, and public values.

4.1.2. Contextualization in Local Settings

The second expected outcome is contextualization in local settings. Knowledge and technologies related to sustainability transitions cannot simply be applied to regions as universal solutions. Decarbonization technologies, renewable energy systems, resource circulation, mobility systems, and agricultural or forestry policies are only meaningful when they are connected to local geographic conditions, industrial structures, demographic trends, lifestyles, cultures, institutions, and residents' values.

This perspective is related to the concept of socially robust knowledge, emphasizing that knowledge should not only be scientifically valid, but also socially trusted and contextually relevant [56]. Transdisciplinary research and technology assessment similarly stress the importance of connecting expert knowledge and technological options with social and local contexts [26,27,33]. In co-learning, contextualization entails that expert knowledge, technologies, and policies are reinterpreted in relation to local resources, everyday issues, future visions, and social constraints.

This outcome is especially central to bridging co-learning, but it is also relevant to the other types. In interdisciplinary co-learning, contextualization is apparent when knowledge from multiple fields is connected to regional problem contexts. In project-based co-learning, it arises when learners understand global environmental issues as local issues. In policy co-learning, it appears when policy goals and institutional options are reconsidered in light of local living conditions and values.

4.1.3. Relational Change

The third expected outcome is relational change. Co-learning goes beyond knowledge exchange; it is also a process through which relationships among participants can change. Among experts and citizens, local governments and residents, businesses and communities, schools and local actors, or researchers from different disciplines, there could be trust, mistrust, expectations, misunderstandings, distance, or fixed role perceptions. In co-learning, participants can come to understand others' positions, knowledge, constraints, and values, which can change their relationships.

The study of science communication and public engagement has repeatedly shown that relationships between experts and nonexperts cannot be reduced to between information providers and receivers [14–16,18]. The study of public dialogue and deliberation also emphasizes the importance for participants of giving reasons, listening to one another, and understanding different perspectives [19,49]. In co-learning, relational change includes not only mutual understanding and mutual trust, but also the articulation of previously invisible conflicts, concerns, dissatisfaction, and differences in values. Disagreement is not only an obstacle to consensus; it can also be an opportunity for participants to reflect on their assumptions and reconsider their problem framings.

Relational change appears differently across the four types of co-learning. In bridging co-learning, it may appear as mutual understanding arising between experts and regional

actors or the articulation of questions and concerns. In project-based co-learning, it may appear as changes in the relationship between learners and local communities. In policy co-learning, it may appear as the reconfiguration of relationships between governments and residents, including trust or mistrust regarding policy processes. In interdisciplinary co-learning, it may appear as the formation of collaborative relationships among researchers from different fields.

4.1.4. Agency Formation

The fourth expected outcome is agency formation. Co-learning outcomes are not limited to changes in knowledge or relationships; they also appear when participants come to view themselves as actors who can engage with regional issues. Agency formation refers to the development of participants' willingness and capacity to contribute to regional sustainability transitions through expression, proposal-making, collaboration, continued participation, or collective action.

Sustainability education emphasizes that learners should not only acquire knowledge but also develop their competencies and motivation to act toward sustainable futures. Wiek et al. [58] identified key competencies in sustainability, including systems-thinking, anticipatory, normative, strategic, and interpersonal competencies. Barth and Michelsen [59] discussed how education can contribute to sustainability science by developing capacities for change.

The formation of agency may appear at different levels. At the initial level, participants articulate questions, concerns, preferences, suggestions, or demands in dialogue. At a more developed level, they may engage in continued participation, collaborative activities, or the formation of new groups and networks. In project-based co-learning, agency formation may appear as students' and young people's sense of contribution to their region and their willingness to participate. In bridging co-learning, it may appear when citizens express their experiences and concerns and engage in problem framing. In policy co-learning, it may appear as residents' and civic actors' ability to participate in policy formation. In interdisciplinary co-learning, it may appear as researchers' and engineers' orientation toward practical engagement with societal problems.

4.2. Analytical Dimensions for Examining Co-Learning Outcomes

The four outcomes discussed above provide analytical perspectives for the examination of co-learning practices. In transdisciplinary research, increasing attention has been paid to assessing collaborative research processes and outcomes in relation to criteria such as relevance, credibility, legitimacy, and effectiveness [60]. Similarly, applying co-learning outcomes in empirical research and evaluation requires translating them into observable aspects. Table 4 summarizes the analytical dimensions, their main meanings, and examples of possible observations.

Table 4. Analytical dimensions and possible observations of co-learning outcomes.

Analytical Dimension	Main Meaning	Examples of Possible Observations
Knowledge integration	Different forms of knowledge, experience, and values are connected, leading to revised problem understanding	References to others' knowledge; combined problem framings; new perspectives; new proposals; connections between expert and local knowledge
Contextualization in local settings	Science, technology, and policy are reinterpreted in relation to local conditions, values, and constraints	References to local resources, livelihoods, everyday issues, industries, institutional constraints, or future visions; reinterpretation of technologies or policies according to local contexts

Relational change	Mutual understanding, mutual trust, and articulation of concerns or conflicts emerge among participants	Recognition of others' perspectives; willingness to continue dialogue; articulation of questions, expectations, concerns, dissatisfaction, conflicts, or value differences
Agency formation	Participants position themselves as actors who can engage with regional issues	Expression of preferences, suggestions, or demands; action intentions; sense of contribution; proposal-making; continued participation; formation of new groups or networks

These observations should not be treated as fixed evaluation criteria that can be mechanically applied to all co-learning practices. In empirical analyses, the relevant dimensions and observations should be adjusted according to the type of co-learning, the participants who are involved, the regional issues that are addressed, and the duration of the practice. For example, in bridging co-learning, the connection between expert and local knowledge, contextualization in local settings, and the articulation of questions and concerns may be especially important. In project-based co-learning, learners' understanding of regional issues, sense of contribution, and agency formation may be more central.

Multiple methods can be combined to analyze co-learning outcomes. Questionnaires can be useful for examining changes in knowledge, attitudes, and action intentions. Interviews and open-ended responses can help clarify the ways in which participants interpret others' knowledge and values. Workshop records, discourse analysis, sticky-note data, coding categories, and outputs produced by participants can provide insights into how knowledge integration and problem reframing take place through dialogue. Participant observation can also help capture the interactional atmosphere of the setting, relationships among participants, opportunities to speak, and nonverbal interactions.

Co-learning outcomes can emerge over a range of time scales. Changes in knowledge or immediate satisfaction can be observed relatively soon, while relational change and agency formation can require longer-term observation. Evaluating co-learning therefore requires not only post-event assessment but also continuous and longitudinal perspectives.

The analysis of co-learning outcomes requires attention to multiple dimensions: knowledge, context, relationships, and agency. This makes it possible to understand co-learning not merely as knowledge transfer, dialogue, participation, or consensus building, but as a process through which diverse actors revise their understandings, relationships, and action possibilities through interaction.

5. Illustrative Application to Co-Learning Practices in Tanegashima, Japan

This section presents an illustrative application of the typology, design principles, and analytical framework proposed in this paper to two co-learning practices in Tanegashima, Kagoshima Prefecture, Japan. The first is a participatory dialogue practice conducted between experts and local residents in relation to regional decarbonization research. The second is a school-based sustainability education program for junior high school students. The former is positioned as an example of bridging co-learning, while the latter is positioned as an example of project-based co-learning.

This section does not aim to report a new empirical study or to present newly analyzed data. Rather, it draws on related empirical studies to illustrate how the proposed framework can be applied to concrete regional sustainability practices. The bridging practice is examined in detail in a related manuscript [61], and the design, implementation, and evaluation of the project-based educational practice have been reported previously

by Yatagawa and Kurishima [13]. In this manuscript, these cases are not reanalyzed as new data; they are used only to demonstrate the applicability of the conceptual and methodological framework.

Tanegashima is an island region located south of Kagoshima Prefecture, Japan. Agriculture, particularly sugarcane production, is one of the island's main industries. The Tanegashima Space Center, located in the southern part of the island, makes Tanegashima a distinctive region where science, technology, and local society intersect. As with many rural and island regions in Japan, Tanegashima faces the challenges of population decline, aging, youth outmigration, and the maintenance of local industries. Against this background, Tanegashima provides an important field for examining co-learning as a basis for sustainability transitions that involve renewable energy, resource circulation, regional mobility, and education.

5.1. Bridging Co-Learning: Dialogue Between Experts and Local Residents on Regional Decarbonization Research

The study of regional decarbonization and resource circulation requires scientific and technical knowledge. However, implementing this knowledge in local society requires connecting it with residents' lived experiences, knowledge of local resources, concerns about the future, and values related to livelihoods and local industry. In Tanegashima, a participatory workshop on regional decarbonization research was organized as a dialogue-based co-learning setting rather than as a one-way lecture. The workshop consisted of short presentations by researchers and experts, small-group discussions among local residents, and plenary sharing of opinions and questions. The expert inputs introduced research topics and future visions related to energy, mobility, agriculture and forestry, and education. After these inputs, local residents discussed these topics in groups and expressed opinions, questions, concerns, expectations, and suggestions from the perspective of their everyday lives and local experience. The workshop involved 24 local residents and 10 researchers, experts, and facilitators.

This practice can be understood as an example of bridging co-learning because it connects expert knowledge with locally situated knowledge. A key point is that residents' questions and concerns should not be treated as signs of insufficient understanding of research or technology. Instead, they should be interpreted as knowledge resources for reconsidering the assumptions, problem framings, and implementation pathways of regional decarbonization.

In relation to the design principles discussed in Section 3, this practice in particular involved diversity and heterogeneity, dialogic fairness, the translation and contextualization of knowledge, and facilitation. The workshop brought together experts and residents with different forms of knowledge and experience, creating opportunities for residents to express questions, concerns, and suggestions in response to expert inputs. These elements of design support the connection between expert knowledge and locally situated perspectives.

In the related empirical study, residents' comments were analyzed with in vivo coding and focused coding [61]. Table 5 uses selected coding categories from that analysis to illustrate the ways in which the analytical dimensions proposed in Section 4 can be applied to bridging co-learning.

Table 5. Relationship between coding categories and analytical dimensions in bridging co-learning.

Analytical Dimension	Examples of Related Coding Categories	Interpretation as Co-Learning
Knowledge integration	New Perspectives; Awareness; Local Knowledge; Problem Identification; Suggestion	Residents connected expert inputs with local knowledge, lived experience, and emerging problem understandings.
Contextualization in local settings	Local Knowledge; Problem Identification; Preference; Demand; Public Concern	Decarbonization and technological implementation were interpreted in relation to local resources, livelihoods, industries, constraints, and values.
Relational change	Question; Affirmation; Discontent; Public Concern	Residents expressed questions, expectations, concerns, and dissatisfaction toward experts and research activities, making issues in the expert–resident relationship visible.
Agency formation	Suggestion; Demand; Preference	Residents articulated desired directions and concrete requests, indicating participation as active contributors to the discussion.

This correspondence indicates that the outcomes of bridging co-learning can be understood not simply as knowledge acquisition or participant satisfaction, but as a process in which residents connect expert knowledge with their local experience and values, express questions and concerns, and engage in problem framing. Categories such as Question, Public Concern, and Discontent, in particular, should not be interpreted only as negative reactions. They can also serve as learning resources for the reconsideration of expert-led research and technological implementation in local contexts.

Here, agency formation appears mainly in the form of residents’ articulation of suggestions, demands, and preferences. At this stage, this should be understood as an initial form of agency in the participation in discussions on regional sustainability, rather than as simple evidence of sustained collective action. In the present paper, the discussion is limited to the illustrative application of the analytical framework. Whether and how such bridging co-learning leads to sustained community visioning or collective action should be examined in future empirical research.

5.2. Project-Based Co-Learning: Fostering Youth Agency Through Regional Sustainability Education

Yatagawa and Kurishima [13] designed, implemented, and evaluated a school-based educational program on regional sustainability in Tanegashima. The program was implemented as part of the formal curriculum for all 169 students in grades 1–3 of junior high school from 2021 to 2023, with approximately 20 class hours allocated over the three years. It combined classroom lectures, group work, backcasting exercises, discussions on regional issues, and student presentations or policy proposals. Students learned about the Sustainable Development Goals (SDGs), climate change, renewable energy, and local sustainability challenges, and then connected these topics to future visions for Tanegashima.

This practice can be understood as an example of project-based co-learning, as students engaged with concrete regional issues and considered the future of their community in relation to their own lives and pathways. The key point here was that students did not merely acquire environmental knowledge. Instead, they learned to interpret regional issues as matters that were connected to their own lives, futures, and possible contributions to the community.

In relation to the design principles discussed in Section 3, this practice particularly involved individual reflection and group dialogue, translation and contextualization of

knowledge, and continuity and feedback. Concepts such as the SDGs, climate change, renewable energy, and backcasting were considered in relation to local issues and future visions in Tanegashima. Repeated learning also provided opportunities for students to reflect on their relationship to the region and to reconsider how they might engage with regional sustainability issues.

Table 6 summarizes how this project-based educational practice corresponds to the analytical dimensions proposed in Section 4.

Table 6. Relationship between analytical dimensions and the project-based co-learning practice.

Analytical Dimension	Manifestation in the Practice	Interpretation as Co-Learning
Knowledge integration	Learning that connected the SDGs, climate change, renewable energy, regional issues, and future visions	School-based knowledge was connected with regional issues, forming a basis for understanding regional sustainability in an integrated way.
Contextualization in local settings	Global environmental issues were connected with Tanegashima's population decline, industries, local resources, and future visions	Environmental issues were understood not as distant problems, but as issues related to the future of the region.
Relational change	Students reconsidered the region not merely as a place of residence, but as a place with which they may be involved in the future	The relationship between learners and the local community was transformed, supporting interest in and attachment to the region.
Agency formation	Changes in students'sense of contribution, attachment to the region, and awareness of future engagement	Learning within school education contributed to the formation of youth agency for future regional engagement.

This correspondence indicates that project-based co-learning frames environmental education not only as knowledge acquisition, but also as a process of contextualized understanding, relational change, and agency formation. The possibility that project-based co-learning may extend beyond formal education into voluntary regional engagement remains an important issue for future longitudinal research.

5.3. Positioning the Two Practices

These two practices illustrate different but complementary forms of co-learning. The bridging practice shows how expert and local knowledge can be connected, how science and technology can be reinterpreted in local contexts, and how residents'squestions and concerns can become resources for problem reframing. The project-based practice shows how locally grounded education can support young people in understanding regional sustainability issues, rethinking their relationship with the community, and developing agency for future engagement.

The two practices also show that different types of co-learning emphasize different design principles. Bridging co-learning requires careful facilitation and translation between expert and local knowledge, whereas project-based co-learning depends more strongly on continuity, reflection, and contextualized learning. At the same time, both practices suggest that co-learning can connect science and technology, environmental education, regional capacity building, and community engagement. In Tanegashima, bridging and project-based co-learning can be understood as complementary elements of a broader basis for regional sustainability transitions.

6. Discussion and Conclusions

This paper conceptualizes co-learning as a multi-actor learning process for regional sustainability transitions. Instead of treating co-learning simply as one-way knowledge

transfer, two-way communication, participation, or consensus building, this paper defines it as a process through which participants with different forms of knowledge and social positions revise their understandings, relationships, and orientations toward action through dialogic and reflective interaction. This framing connects environmental education, citizen engagement, science communication, knowledge co-production, transdisciplinary research, technological contextualization, regional capacity building, and policy formation within a broader conceptual framework. Figure 1 summarizes the relationships among diverse actors, the four types of co-learning, the cross-cutting design principles, and the expected outcomes discussed in this paper. It also distinguishes primary and secondary relationships between types of co-learning and the analytical dimensions of outcomes.

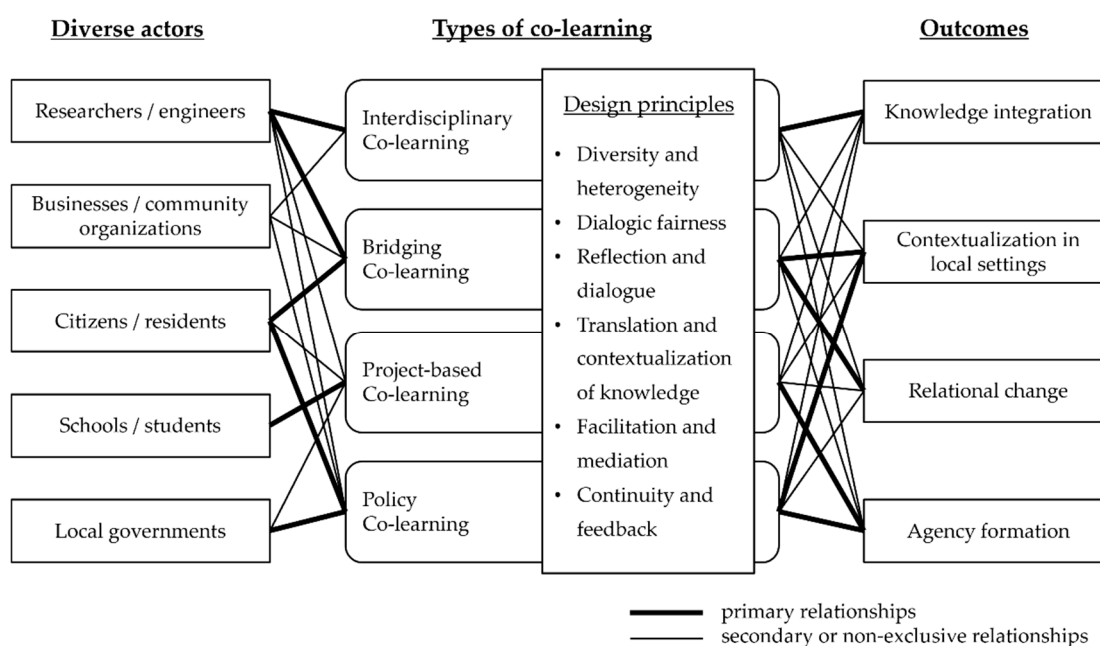


Figure 1. Relationships among diverse actors, types of co-learning, design principles, and expected outcomes.

The main contribution of this paper is not the introduction of a new term or an entirely new practice. Rather, it lies in organizing dispersed discussions and practices into a framework that makes co-learning easier to design, compare, and analyze in the context of regional sustainability transitions. From this perspective, participatory dialogue, environmental education, technology assessment, community-based projects, and policy-oriented learning can be understood as related forms of co-learning when they involve the mutual revision of understandings, relationships, and orientations toward action.

A central implication of this definition is that the questions, concerns, disagreement, dissatisfaction, and knowledge based on lived experience of nontechnical participants should not be treated merely as obstacles to the social implementation of science, technology, or policy. Instead, they are better understood as resources for the reframing of problems and the contextualization of technologies and policies. At the same time, experts and researchers are also positioned as learners who may need to reconsider their research questions, technological assumptions, assessment criteria, and implementation pathways through interaction with citizens and regional actors. Thus, co-learning provides a way to understand environmental education and citizen engagement not merely as processes for improving public understanding, but as reciprocal processes of learning and transformation.

This paper also proposes a methodological framework for the design and analysis of co-learning practices. The four types of co-learning—interdisciplinary, bridging, project-based, and policy co-learning—allow different actor relationships and knowledge interfaces to be distinguished while also recognizing their potential connections. The six design principles—diversity and heterogeneity, dialogic fairness, reflection and dialogue, translation and contextualization of knowledge, facilitation and mediation, and continuity and feedback—identify conditions that can support meaningful co-learning. The four analytical dimensions—knowledge integration, contextualization in local settings, relational change, and agency formation—provide appropriate perspectives for the examination of outcomes without reducing co-learning to participant satisfaction, knowledge acquisition, or the formation of consensus.

The two practices in Tanegashima illustrate the possible application of this framework. Participatory dialogue on regional decarbonization research shows how expert knowledge and local knowledge can be connected, as well as how residents' questions, concerns, and dissatisfaction can function as learning resources for reconsidering expert-led research and technological implementation in local contexts. In this sense, the influence of co-learning on technical problem-solving should be understood not as a direct resolution of specific technical problems but as a broadening of problem framings and the clarification of social implementation conditions, including local resources, livelihoods, industries, constraints, and values. The school-based sustainability education program shows that young people can connect the SDGs, climate change, renewable energy, regional issues, and future visions with their own lives and future pathways. Together, these practices indicate that co-learning can form the basis for connecting science and technology, environmental education, regional capacity building, and community engagement.

This paper has several limitations. First, because the main purpose of this paper is to develop a conceptual and methodological framework, it does not provide a detailed empirical analysis or evaluation of the Tanegashima practices. The illustrative cases are used to clarify the applicability of the proposed framework rather than to test its effectiveness or to assess the long-term outcomes of co-learning. Future empirical research is therefore needed to examine how the proposed framework can be applied, refined, and evaluated in concrete regional contexts. Second, the typology, design principles, and analytical dimensions proposed here should be understood as an initial framework rather than as a fixed model applicable to all regions and issues. Third, co-learning outcomes may emerge over a range of time scales: changes in knowledge or immediate perceptions can be observed relatively quickly, while relational change, agency formation, sustained engagement, and institutional change require longer-term observation. Comparative and longitudinal research across regions, policy domains, and actor configurations would help clarify the usefulness and limitations of this framework.

Further research should also investigate how different types of co-learning can be connected over time. Mutual understanding developed through bridging co-learning could lead to community visioning or policy formation, while agency formed through project-based co-learning may develop into youth-led community activities or participation in regional decision-making. These processes suggest that co-learning should be understood not as a single event, but as a cumulative and iterative basis for regional transformation. To support this, further work is needed on the spaces, methods, facilitators, evaluation approaches, and institutional arrangements that can allow co-learning to be sustained and adapted to different local contexts.

Regional sustainability transitions cannot be achieved through technologies or policies alone. They require processes through which diverse actors can learn from one another, question each other's assumptions, build relationships, and expand possibilities for

action. By proposing a conceptual and methodological framework for co-learning, this paper contributes to understanding how environmental education and citizen engagement can empower local actors through science and collaborative learning. It also clarifies how such learning-based approaches can support transitions toward sustainable and resilient communities.

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