Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Transdisciplinary learning as a key leverage for sustainability transformations

Matthias Barth[1,2], Amanda Jiménez-Aceituno[3,4], David PM Lam[1,4], Lina Bürgener[1] and Daniel J Lang[1,5]

Learning and transdisciplinary research are widely acknowledged as key components for achieving sustainability; however, the links between these concepts remain vague in the sustainability literature. Recently, emphasis has been given to transdisciplinary learning, highlighting its potential as an approach that contributes to solving real-world problems. To better understand and foster transdisciplinary learning for sustainability transformations, it is relevant to pay attention to two dimensions that define transdisciplinary learning: *social interaction* (individual learning in a social setting, as a group, or beyond the group), and *learning forms* (single-, double-, or triple-loop learning). This article introduces a conceptual framework built upon these two dimensions to understand three specific forms of transdisciplinary learning as a) individual competence development, b) experience-based collaboration, and c) societal interaction. This framework helps to clarify the design of learning processes as well as their interactions in transdisciplinary processes to support transformative change.

Addresses
[1] Institute for Sustainable Development and Learning (ISDL), Leuphana University of Lüneburg, Germany
[2] Eberswalde University for Sustainable Development, Germany
[3] Stockholm Resilience Centre, Stockholm University, Sweden
[4] Social-Ecological Systems Institute (SESI). Leuphana University of Lüneburg, Germany
[5] Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology, Germany

Corresponding author: Lang, Daniel J (daniel.lang@kit.edu)

Current Opinion in Environmental Sustainability 2023, **64**:101361

This review comes from a themed issue on **Open Issue**

Edited by **Opha Pauline Dube, Victor Galaz** and **William Solecki**

For complete overview of the section, please refer to the article collection, "Open Issue"

Available online 5 September 2023

Received: 6 May 2022; Revised: 27 July 2023;
Accepted: 8 August 2023

https://doi.org/10.1016/j.cosust.2023.101361

Unlearning unsustainability

The sixth assessment report of the Intergovernmental Panel on Climate Change in 2021, clearly pointed out that the scale of recent changes across the climate system is unprecedented in human history, with human-induced climate change affecting weather and climate extremes in every global region [1]. These developments threaten the very idea of the concept of sustainable development as a way to navigate pathways into a safe and just space for humanity, in which planetary boundaries are respected and social boundaries constituting basic human rights are taken care of [2]. Sustainable development has gradually found its way into academic discourse and has led to the emergence of sustainability science as a field of its own [3]. From the beginning, conceptions of sustainable development were predominantly grounded in an understanding of what is *unsustainable*, and defined less as a specific goal to be achieved, but rather as an ongoing process of change — that is, as a moving target that necessitates communication and deliberation [4].

Not surprisingly, learning and education are considered essential means for achieving sustainability goals, such as the UN Sustainable Development Goals, besides 'hard' instruments such as regulations and economic measures [5]. Consequently, the notion of learning for sustainability figures prominently in both academia and policy and has been used in a broad sense to capture the whole spectrum of informal, nonformal, and formal learning. Mutual societal learning processes with an emphasis on the transdisciplinary nature of such learning have been increasingly mentioned as a central concept to foster sustainability transformations [6,7]. Arjen Wals [8] aptly pointed out that 'learning our way out of unsustainability' might play a crucial role for such transformations.

While the importance of learning and education has been repeatedly emphasized [9], the increasing use of the concept in a wide range of different contexts and fields is not without its problems, as the concept of learning has remained rather vague [10,11]. For example, Reed et al. [12] highlighted the lack of clarity in the use

of social learning as a concept in natural resource management, Jiménez et al. [13,14] pointed to the confusion between different educational strategies implemented in biodiversity conservation initiatives, and the literature on sustainable transformations refers to shifts in mindsets or paradigms without explicitly connecting this to educational and learning processes [15]. With this article, we want to contribute to clarifying the role, forms, and contributions of learning for sustainability by introducing a conceptual framework of transdisciplinary learning, and elaborating on how an informed understanding of learning processes for sustainability can guide action and further research.

Transdisciplinary learning — a conceptual framework

To be able to utilize the concept of transdisciplinary learning to inform activities in both practice and research, clarity is needed on the two building blocks of learning and transdisciplinarity, respectively, and on specific forms of such learning, and their differences and characteristics.

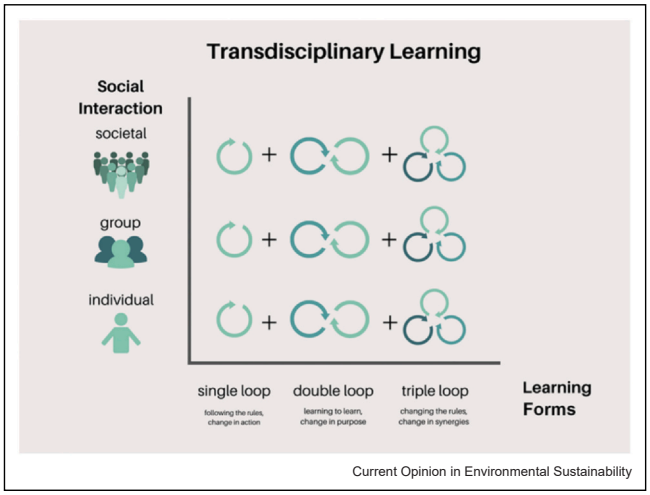
Looking at the literature on learning for sustainable development, one central challenge is a problematic confusion between learning as a process and as an outcome of that process. From a learning science perspective, it is emphasized that learning is first and foremost a lifelong and constant process for one or more individuals, as it is impossible for us not to learn [16]. In a pragmatic approach, this has been taken in the literature to define learning as a process that leads to cognitive change and manifests as behavioral change [12]. However, this view has been contested through research on the development of mental models, which argues that learning happens when cognitive changes occur, for instance, when new knowledge has been acquired, or a shift in an individual's perception has taken place, neither of which necessarily leads to changes in behavior [17]. Learning then can be understood as a process of cognitive changes that leads to new knowledge, perceptions, or competencies, which in turn may be translated to changes in action and behavior. Such learning is apparent in individuals as well as among learners in groups, can happen in formal, informal, and nonformal settings, and especially in transdisciplinary processes, the question who is learning in the process needs to be defined for each specific context.

Particularly in the sustainability science discourse, 'transdisciplinarity' has been defined as a research practice or principle that (i) takes real-world problems as a starting point, (ii) acknowledges context-dependencies related to these problems, (iii) differentiates and integrates knowledge from different domains, inside and outside academia, which are relevant for addressing the problems, and (iv) aims to contribute to solving concrete real-world problems as well as generating scientific insights beyond these problems (see [18,19]). For the purpose of this paper, we use a broad notion of 'research practice', as an evidence-based learning process that integrates different forms of knowledge. Accordingly, mutual- learning processes have often been declared as essential characteristics of transdisciplinary processes [20]. Westberg and Polk [21] introduce the theory of situated learning to the discourse on transdisciplinarity and add a more nuanced perspective on learning in transdisciplinary processes. Furthermore, in their literature review on knowledge-related concepts in sustainability science, Apetrei et al. [11] derived knowledge for and through learning as one entry point to how knowledge is conceptualized in the literature. This further differentiates social learning and sustainability learning as concepts, and in so doing provides more structure in the learning discourse closely related to transdisciplinarity.

To further conceptualize transdisciplinary learning and to better position and distinguish different forms of how such learning occurs, we draw on a framework based on a distinction between two main dimensions of learning [4]: a) the social interaction, and b) the learning forms regarding the level of reflection about the learning process (Figure 1).

Turning toward the social dimension of learning, we can distinguish three distinctive forms, ranging from individual learning in a social setting, to learning as a group, and to settings that transcend group boundaries.

Figure 1



Two dimensions to understand transdisciplinary learning: social interaction (individual, group, and societal), and learning forms (single-, double-, and triple-loop).
Based on Figure 12.1 in Barth 2015 [4].

The first and probably most traditional understanding of *individual learning* refers to learning that happens individually but in a social setting. Here, learning happens by processing information, reflecting on how one's own interests are related to those of others, and building relationships, while being involved in collaborative processes in transdisciplinary settings. Such learning is influenced by the cultural context and the formal or informal social settings in which learning takes place [22,23]. *Learning as a group* goes beyond the learning process of individuals, emphasizing that not only individuals but also social units (such as organizations) are able to achieve a learning outcome that is more than the sum of individual learning [24]. Such group learning is captured most often as organizational learning for sustainability [25], but is also reflected in learning in communities of practice [26,27] or loosely coupled networks [28]. Finally, learning might also *transcend group boundaries* and diffuse to wider social units, triggering system-wide change processes. Such societal learning, that is, learning *as* a society rather than just learning *in* society ('social learning'), is seen as a driver for change that can move the social–ecological system toward more sustainable trajectories [29].

Different forms of learning can also be distinguished within all three forms of social interaction. Here, we refer to single-, double-, and triple-loop learning — terms that refer to the level of reflection that informs the learning process, as popularized in management science by Argyris and Schön [30]. *Single-loop learning* may be understood as learning by reconsidering decisions made in light of new information ('doing things differently'). Its aim is to bring about more effective or efficient action, while relying on an unchanged set of values and beliefs. *Double-loop learning* in contrast involves the re-evaluation of the underlying assumptions and beliefs that informed a given decision ('doing different things'); it is about changing the rules rather than changing one's responses within a given set of rules. *Triple-loop learning* represents the third and most far-reaching approach. It refers to the recursive practice of learning about the process of learning itself, and involves developing new ways of thinking, and methodologies to support the reframing and transformation that takes place in double-loop learning.

If we analyze transdisciplinary learning against these two axes of social interaction and specific learning forms, we can distinguish between conceptions of transdisciplinary learning in a systematic way. Such a classification clearly involves some simplification, and it is a matter for debate where the boundaries for the respective approaches should be drawn. Nevertheless, it helps to depict specific forms of transdisciplinary learning and to elaborate on characteristics of the learning process, as well as differences and similarities of the learning outcomes. In what follows, we want to introduce and discuss three specific conceptions.

Transdisciplinary learning as individual competence development

Individual learning is commonly understood as a process involving a change in an individual's behavior or knowledge [31] that can occur on different levels of societal interaction in formal, informal, and nonformal settings. Particularly when it comes to learning processes in relation to sustainability transformations, these settings are often interlinked and all play a crucial role. In the context of transdisciplinary learning, we especially aim to develop a specific individual skill set to actively shape sustainable development.

This means that we generally aim to build knowledge about (un)sustainable development as well as its causes, effects, and interrelations, and, as a further step beyond mere knowledge acquisition, to achieve a certain level of (self-)reflection, leading to a change of behavior toward active participation in shaping sustainable development. Transdisciplinary learning adds another layer by integrating a broad range of expertise drawn from various actors in science and society, and is therefore highly context-dependent and emergent. It allows for co-design processes and hence offers different levels of reflection that may lead to single-, double-, as well as triple-loop learning.

When it comes to formal learning settings, competency-based approaches play a central role [32], targeting specific learning outcomes that are supported by learning processes in particular learning settings. Competencies in this sense are widely understood as the interaction among knowledge, skills, and attitudes (or willingness) that enable learners to cope successfully and responsibly with changing situations in a certain domain, by also reflecting on the experience gained [33]. In an exploratory literature review, van Poeck et al. [34] distinguish between three different learning outcomes in current research on sustainability transitions: *Conceptual learning outcomes* are the most frequently identified and mainly focus on knowledge, but also include values and norms or visions and commitment. *Practical learning outcomes* lay emphasis on a contribution to "some form of sustainability change agency, as well as to more sustainable habits, behavior, technologies, practices or even regimes". *Relational learning outcomes* consider, for example, the development of networks, but is an outcome category that is rarely used. Learning outcomes on an individual level can be assessed, for example, using a context-specific mixed-methods competence assessment, measuring the development of not just knowledge, but also aspects such as volition and attitudes [35]. According to Scherak & Rieckmann [36], assessment methods need to be "constructively aligned with the

intended learning outcomes and the relevant teaching and learning practices" (p. 124). Redman et al.'s [37] typology of eight assessment tools can help to make informed decisions about how to assess individual competence development (e.g. reflective writing, performance observation, and scenario/case test).

Transdisciplinary learning as experience-based collaboration

Transdisciplinary learning also occurs as part of group learning and organizational processes in experience-based collaborations or a Community of Practice (CoP). These learning processes can happen in formal learning settings but more often occur in informal or nonformal settings. A CoP requires a group of people interacting regularly through informal learning activities (e.g. conversations, workshops, and learning by doing) to foster knowledge creation and sharing in a specific domain of interest [38]. Importantly, these communities are based on shared practice, which involves actively testing ideas to address specific problems and learn how to do things better [39], and require the establishment of collegial or personal relations based on trust [40].

In their role of addressing real-world problems, CoPs need to continuously reflect on whether specific actions and approaches are working or not to guide future actions (single-loop learning), as well as include a variety of participants with different stocks of knowledge [40]. Transdisciplinary CoPs [39] share these characteristics, but are formed by heterogeneous members with a variety of experiences and knowledge, drawn from different disciplines, institutions, and societal domains. This diversity generates more opportunities for reflection upon different theoretical and methodological perspectives, backgrounds, and worldviews guiding the practice of the group (double-loop learning).

There are many types of transdisciplinary CoP regarding, for example, size or scale (local, national, and international), ways of interaction (face-to-face, online, and hybrid), or the domain of interest. Transdisciplinary CoPs that focus on addressing sustainability issues are often designed as science-practice or science-society interfaces where researchers and practitioners learn together to find solutions to sustainability challenges. These solutions are commonly designed at a technical level of action (e.g. to learn about specific tools or frameworks for natural resources management [41,42]); but also at the social level (e.g. developing sustainability-related competencies for current or future educators [43–45]), the cultural level (e.g. management practices in marine-protected areas integrating the culture and traditions of local and indigenous communities [46]), and other levels of action [47].

One of the most influential transdisciplinary CoPs is the Intergovernmental Science-Policy Platform of Biodiversity and Ecosystem Services (IPBES), which constitutes a space for individual and organizational learning [48]. IPBES is an independent intergovernmental community seeking to develop knowledge to inform and foster knowledge-based policies to secure biodiversity and well-being. Knowledge generation in IPBES aspires to be inclusive, meaning to include diverse forms of knowledge from a broad range of actors [49]. However, IPBES faces a range of challenges to implementing this inclusive approach (see, e.g. [49–51]). Similarly, at a lower (national) scale, Dendoncker et al. [52] analyzed the impact of the Belgium Ecosystems Service CoP, and found that although different stakeholders and values were usually accounted for, genuine transdisciplinary studies in which knowledge is coproduced between researchers and practitioners were still to be undertaken.

Transdisciplinary learning as societal interaction

Transdisciplinary learning beyond individuals and group boundaries can enable societal learning, which is utterly important for triggering systemic change toward sustainability. Some authors have improved our understanding of the learning that occurs between researchers and practitioners within transdisciplinary projects (e.g. [20,47,53]). In addition, Adler et al. [54] propose to conceptualize the transfer of knowledge across transdisciplinary projects as 'arguments by analogy', and Wuelser et al. [55] differentiate between seven types of transferable knowledge (i.e. transdisciplinary principles, transdisciplinary approaches, systematic procedures, product formats, experiential know-how, framings, as well as insights, data, and information).

However, less literature has focused on how transdisciplinary learning occurs beyond individuals and groups, and thus beyond transdisciplinary projects in the sense of societal learning that triggers systemic change [15,56]. On a societal level, transdisciplinary learning can support collectivizing engagement of diverse actors from different contexts to build momentum for systemic change, through socializing insights from context-specific mutual- learning processes (e.g. within a specific project). Such insights can stem from informal single-, double-, and triple-loop learning processes and foster societal learning beyond transdisciplinary projects in the sense of third-order effects [57]. For example, practitioners engaging and learning in transdisciplinary processes will make decisions that can influence the systems in which they operate (e.g. food companies or farmers influencing the food system).

Transdisciplinary learning on a societal level can also be fostered through amplifying insights from individual education processes and experience-based

collaborations. Amplification is a concept in sustainability transformations literature, which describes processes that can scale insights within, outside, or beyond the process to foster transformative change toward sustainability [58,59]. For example, by disseminating principles and approaches that have worked in a project to other projects in different contexts, or by influencing norms and beliefs in the study region of a transdisciplinary project. Through amplification, insights can become confirmed and consolidated with other people, ultimately becoming institutionalized to facilitate behavior change that supports the realization of sustainability [60]. In addition, despite being context-specific, insights from single-, double-, and triple-loop learning can diffuse translocally and inform shared ideas, activities, and objectives that foster transformative change across and beyond transdisciplinary research projects [61]. Indeed, context-specific insights can inform people beyond local contexts, such as global sustainability initiatives and discourses [62].

Outlook and future research

Transdisciplinary research in sustainability science has been characterized as a knowledge coproduction process, in which a variety of actors from science and other areas of society (e.g. government or practitioners) interact in mutual-learning processes to develop, test, and implement solutions to real-world problems that foster transformative change. Despite emphasizing the relevance of learning in transdisciplinary settings, much of the literature has neglected to include insights from learning theories (see e.g. [10]), especially concerning the mutual-learning processes that are fundamental for transdisciplinary research. Some authors have made progress in understanding how learning occurs in transdisciplinary projects (e.g. [21,47]) as well as how to learn about transdisciplinary practices in general [63,64]. By discussing how including a learning perspective can enrich research that seeks to understand and foster *transdisciplinary learning* happening at different levels of social interaction (individual, group, and societal) and learning forms (single-, double-, and triple-loop), we want to both make a contribution to and further develop existing approaches.

Strengthening transdisciplinary processes by more deeply considering learning perspectives

Learning is a key element in transdisciplinary research, particularly regarding mutual-learning and integration processes [20,65]. As outlined above, transdisciplinary learning processes can happen and stimulate learning on all three levels (individual, group, and societal), and have the potential to enable people, both individually and as collectives, to change their behavior and act, by gaining the necessary sustainability competencies [66,67]. Including insights from learning theories, such as individual sustainability competence development (building knowledge, skills, and attitudes), and learning in CoPs can enrich transdisciplinary research in its endeavor to foster transformative change. This would mean addressing the design of transdisciplinary projects (e.g. adaptation of formats and methods, or planning of societal and scientific effects) to more deeply consider learning processes on these levels. For example, when planning workshops in which researchers and practitioners participate, the workshop processes should not only focus on genrating general outcomes (e.g. artifacts), but also on 'effective' learning processes, leading to certain learning outcomes at different societal levels [58]. This can be done by offering time and space for reflection on the process, and not only the outcomes [4,68], and accepting failures as part of the (learning) process [69]. Such formats can also play an important role for competence development in more formal educational settings to prepare future change agents to engage in and lead transdisciplinary processes [70].

Transdisciplinary learning for transformative change

Learning has been mentioned in several transformation frameworks (e.g. transition management [71], social–ecological transformations [72]), but often without a thorough inclusion of learning theories or an emphasis on transdisciplinary aspects of learning. Including a learning paradigm in the discussion of transformations bears new potential for research and action. It puts emphasis on learning processes that enable actors to be prepared to adapt to new (sustainability) challenges, even in times of crises (e.g. Covid-19, climate change). Despite more reflexive and evolutionary approaches in recent transformations and transition literature (e.g. [73]), much of the literature is dominated by a seeming 'planning paradigm' that emphasizes that we can plan urgently needed transformations. However, this is only possible to a certain extent, as fundamental system change is also about *learning how to learn* (triple-loop learning), which generates the resilience needed to face increasingly uncertain futures. In this context, the generation of strong networks of actors with different expertise (e.g. knowledge systems including indigenous and local knowledge), worldviews (e.g. cosmovisions), and influence in the systems, can be strengthened by establishing transdisciplinary learning processes.

To enable *deliberate* transformative change that is not only planned, but also reflexive, resilient, and learning-oriented, we need to create spaces in which transdisciplinary learning (individual, group, and societal; single-, double-, and triple-loop) can take place. A promising example in this regard are real-world laboratories, or similar research and learning settings [74,75]. Thus, as learning happens along transformations, more research is needed to improve the design of transdisciplinary learning spaces for science and society.

Concluding remarks

Fostering sustainability transformations requires learning from, for, and with diverse societal actors, both formally and informally as well as individually and collectively. The proposed framework provides a structure to better understand and enable such learning processes, through considering both the different levels of interaction and specific learning forms. While it is conceptually helpful to distinguish the levels and forms of learning, it is evident that they are highly interconnected. A deliberate and iterative process of distinguishing the levels and forms of learning seems to be a promising way to use their full potential. Taking learning seriously, the proposed framework can contribute to continuously developing our understanding and practice of transdisciplinary learning for sustainability.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

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

Acknowledgements

DPML and DJL were supported by the project "tdAcademy — Platform for Transdisciplinary Research and Studies", funded by the German Federal Ministry of Education and Research (BMBF) within the framework of the strategy Research for Sustainability (FONA) *www.fona.de/en* as part of its *Social–Ecological Research* funding priority, funding no. Fkz 01UV2070A.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. IPCC: **Climate Change 2021: the Physical Science Basis. Contributions of Working Group 1 to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. Cambridge Univ. Press; 2021.

2. Leach M, Raworth K, Rockström J: **Between social and planetary boundaries: navigating pathways in the safe and just space for humanity**. In: *World Social Science Report 2013. Changing Global Environments*. Edited by UN Educational SaCO(U), International Social Science Council. 2013 OECD Publishing and UNESCO Publishing; 2013:84-89, , https://doi.org/10.1787/9789264203419-en

3. Mooney H: **Editorial overview: sustainability science: social–environmental systems (SES) research: how the field has developed and what we have learned for future efforts**. *Curr Opin Environ Sustain* 2016, **19**:v-xii, https://doi.org/10.1016/j.cosust.2016.05.002

4. • Barth M: Implementing Sustainability in Higher Education: Learning in an Age of Transformation. Routledge; 2015, https://doi.org/10.4324/9780203488355 (Routledge studies in sustainable development).
This book provides in-depth insights into higher education for sustainable development and can serve as a guide and inspiration for various actor groups to engage in this field and to foster transformation processes.

5. Jackson T, Michaelis L: **Policies for Sustainable Consumption: A Report to the Sustainable Development Commission**. Sustainable Development Commission 2003,.

6. •• Wiek A, Kay B: **Learning while transforming: solution-oriented learning for urban sustainability in Phoenix, Arizona**. *Curr Opin Environ Sustain* 2015, **16**:29-36, https://doi.org/10.1016/j.cosust.2015.07.001.
In this article the authors present insights form a solution-oriented sustainability learning course, a specific form of transdisciplinary learning on the indivudual level with links to other levels, and derive some relevant lessons for stakeholders in higher-education that want to engage in similar activities.

7. Scholz RW, Lang DJ, Wiek A, Walter AI, Stauffacher M: **Transdisciplinary case studies as a means of sustainability learning. Historical framework and theory**. *Int J Sustain High Educ* 2006, **7**:226-251.

8. Wals AEJ: **Learning our way out of unsustainability: the role of environmental education**. In *The Oxford Handbook of Environmental and Conservation Psychology*. Edited by Susan D, Clayton SD. Oxford University Press; 2012.

9. Wals AEJ: **Learning our way to sustainability**. *J Educ Sustain Dev* 2011, **5**:177-186, https://doi.org/10.1177/097340821100500208

10. • van Mierlo B, Halbe J, Beers PJ, Scholz G, Vinke-de Kruijf J: **Learning about learning in sustainability transitions**. *Environ Innov Soc Transit* 2020, **34**:251-254, https://doi.org/10.1016/j.eist.2019.11.001.
This editorial provides a very good overview and embedding of the articles covered in a special issue particularly focusing on the connection "between well-established learning traditions and sustainability transition".

11. Apetrei CI, Caniglia G, von Wehrden H, Lang DJ: **Just another buzzword? A systematic literature review of knowledge-related concepts in sustainability science**. *Glob Environ Change* 2021, **68**:102222, https://doi.org/10.1016/j.gloenvcha.2021.102222

12. Reed MS, Evely AC, Cundill G, Fazey I, Glass J, Laing A, Newig J, Parrish B, Prell C, Raymond C, Stringer L: **What is social learning?** *Ecol Soc* 2006, **15**:r1([online] URL:. Response to Pahl-Wostl. 2006. "The Importance of Social Learning in Restoring the Multifunctionality of Rivers and Floodplains.". Ecology and Society 2010, 15:r1.), https://www.jstor.org/stable/26268235.

13. Jiménez A, Díaz MJ, Monroe MC, Benayas J: **Analysis of the variety of education and outreach interventions in biodiversity conservation projects in Spain**. *J Nat Conserv* 2015, **23**:61-72, https://doi.org/10.1016/j.jnc.2014.07.002

14. Jiménez A, Iniesta-Arandia I, Muñoz-Santos M, *et al*.: **Typology of public outreach for biodiversity conservation projects in Spain**. *Conserv Biol* 2014, **28**:829-840, https://doi.org/10.1111/cobi.12220

15. Abson DJ, Fischer J, Leventon J, Newig J, Schomerus T, Vilsmaier U, von Wehrden H, Abernethy P, Ives CD, Jager NW, Lang DJ: **Leverage points for sustainability transformation**. *Ambio* 2017, **46**:30-39, https://doi.org/10.1007/s13280-016-0800-y

16. Bransford JD, Barron B, Pea RD, Meltzoff A, Kuhl P, Bell P, Stevens R, Schwartz DL, Vye N, Reeves B, Roschelle J, Sabelli NH: **Foundations and opportunities for an interdisciplinary science of learning**. In: *The Cambridge Handbook of the Learning Sciences*. Edited by Sawyer RK. 2006 Cambridge Univ. Press; 2006:19-35.

17. Klieme E, Hartig J, Rauch D: **The concept of competence in educational contexts**. In: *Assessment of Competencies in Educational Contexts*. Edited by Hartig J, Klieme E, Leutner D. 2007 Hogrefe & Huber Publishers; 2007:3-22.

18. •• Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ: **Transdisciplinary research in sustainability science: practice, principles, and challenges**.

Sustain Sci 2012, **7**:25-43, https://doi.org/10.1007/s11625-011-0149-x.
Building on experiences in diverse contexts, the paper introduces core principles of transdisciplinary sustainability research structured along an ideal-typical model of transdisciplinary processes.

19. •• Lam DPM, Freund ME, Kny J, Marg O, Mbah M, Theiler L, Bergmann M, Brohmann B, Lang DJ, Schäfer M: **Transdisciplinary research: towards an integrative perspective**. *243 Gaia* 2021, **30**:243-249.
The paper provides an overview of four key aspects of transdisciplinary research including relevant research questions to be answered with regard to the single aspects but also in order to foster an integrative perspective accross the different aspects.

20. • Vilsmaier U, Engbers M, Luthardt P, Maas-Deipenbrock RM, Wunderlich S, Scholz RW: **Case-based Mutual Learning Sessions: knowledge integration and transfer in transdisciplinary processes**. *Sustain Sci* 2015, **10**:563-580, https://doi.org/10.1007/s11625-015-0335-3.
The authors introduce formats of case-based Mutual Learning Sessions and exemplify and reflect their application in a concrete international project context.

21. Westberg L, Polk M: **The role of learning in transdisciplinary research: moving from a normative concept to an analytical tool through a practice-based approach**. *Sustain Sci* 2016, **11**:385-397.

22. Stauffacher M, Walter AI, Lang DJ, Wiek A, Scholz RW: **Learning to research environmental problems from a functional socio-cultural constructivism perspective: the transdisciplinary case study approach**. *Int J Sustain High Educ* 2006, **7**:252-275, https://doi.org/10.1108/14676370610677838

23. Biberhofer P, Rammel C: **Transdisciplinary learning and teaching as answers to urban sustainability challenges**. *Int J Sus High Ed* 2017, **18**:63-83, https://doi.org/10.1108/IJSHE-04-2015-0078

24. Smith PAC: **The importance of organizational learning for organizational sustainability**. *Learn Organ* 2012, **19**:4-10, https://doi.org/10.1108/09696471211199285

25. Siebenhüner B, Arnold M: **Organizational learning to manage sustainable development**. *Bus Strat Environ* 2007, **16**:339-353, https://doi.org/10.1002/bse.579

26. Bradbury S, Middlemiss L: **The role of learning in sustainable communities of practice**. *Local Environ* 2015, **20**:796-810, https://doi.org/10.1080/13549839.2013.872091

27. Krzywoszynska A: **Making knowledge and meaning in communities of practice: What role may science play? The case of sustainable soil management in England**. *Soil Use Manag* 2019, **35**:160-168, https://doi.org/10.1111/sum.12487

28. Newig J, Günther D, Pahl-Wostl C: **Synapses in the network: learning in governance networks in the context of environmental management**. *Ecol Soc* 2010, **15**:24, https://doi.org/10.5751/ES-03713-150424 150424.

29. Fischer J, Riechers M: **A leverage points perspective on sustainability**. *People Nat* 2019, **46**:115-119.

30. Argyris C, Schön DA: Organizational learning II: Theory, Method, and Practice. Addison-Wesley Pub; 1996 (Organization development series).

31. Novarese M: **Individual learning**. In *Encyclopedia of the Sciences of Learning*. Edited by Seel NM. Springer; 2012, , https://doi.org/10.1007/978-1-4419-1428-6_291

32. Wilhelm S, Förster R, Zimmermann AB: **Implementing competence orientation: towards constructively aligned education for sustainable development in university-level teaching-and-learning**. *Sustainability* 2019, **11**:1891, https://doi.org/10.3390/su11071891

33. Weinert FE: **Concept of competence: a conceptual clarification**. In *Defining and Selecting Key Competencies*. Edited by Rychen DS, Salganik LH. Hogrefe und Huber; 2001:45-65.

34. Van Poeck K, Östman L, Block T: **Opening up the black box of learning-by-doing in sustainability transitions**. *Environmental Innovation and Societal Transitions* 2020, **34**:298-310, https://doi.org/10.1016/j.eist.2018.12.006

35. Asbrand B, Martens M: **Qualitative Kompetenzforschung im Lernbereich Globale Entwicklung. Das Beispiel Perspektivenübernahme**. In *Bildung für nachhaltige Entwicklung. Lebenslanges Lernen, Kompetenz und gesellschaftliche Teilhabe*. Edited by Rode H, Overwien B. Ökologie und Erziehungswissenschaft; 2013:47-67.

36. Scherak L, Rieckmann M: **Development and assessment of ESD competences: staff training at the University of Vechta**. In *Competences in Education for Sustainable Development. Critical Perspectives*. Edited by Vare P, Lausselet N, Rieckmann M. Springer International Publishing; 2022:121-128.

37. • Redman A, Wiek A, Barth M: **Current practice of assessing students' sustainability competencies: a review of tools**. *Sustain Sci* 2021, **16**:117-135, https://doi.org/10.1007/s11625-020-00855-1.
Based on a comprehensive literature review, this article presents eight tools for asseessing sustainability competencies in a structured way including strenghts, weeknesses and potentials for improvement.

38. Wenger-Trayner E., Wenger-Trayner B.: **Communities of practice: a brief overview of the concept and its uses**. *Wenger- Trayner, California*. 2015. Available from ⟨http://wenger-trayner.com/introduction-to-communities-of-practice⟩ (accessed April 2022).

39. Cundill G, Roux DJ, Parker JN: **Nurturing communities of practice for transdisciplinary research**. *Ecol Soc* 2015, **20**:22, https://doi.org/10.5751/ES-07580-200222

40. Snyder WM, Wenger E: **Our world as a learning system: a communities-of-practice approach**. Social Learning Systems and Communities of Practice. Springer; 2010:107-124, https://doi.org/10.1007/978-1-84996-133-2_7

41. Garrett KA: **Impact network analysis and the INA R package: decision support for regional management interventions**. *Methods Ecol Evol* 2021, **12**:1634-1647, https://doi.org/10.1111/2041-210X.13655

42. Searle R, McBratney A, Grundy M, *et al*.: **Digital soil mapping and assessment for Australia and beyond: a propitious future**. *Geoderma Reg* 2021, **24**:e00359, https://doi.org/10.1016/j.geodrs.2021.e00359

43. Alkaher I, Avissar I: **Assessing the impact of a program designed to develop sustainability leadership amongst staff members in higher education institutes: a case study from a community of practice perspective**. *Environ Educ Res* 2018, **24**:492-520, https://doi.org/10.1080/13504622.2017.1291799

44. Pedersen KW: **Supporting collaborative and continuing professional development in education for sustainability through a communities of practice approach**. *Int J Sustain High Educ* 2017, **18**:681-696, https://doi.org/10.1108/IJSHE-02-2016-0033

45. Bürgener L, Barth M: **Sustainability competencies in teacher education: making teacher education count in everyday school practice**. *J Clean Prod* 2018, **174**:821-826, https://doi.org/10.1016/j.jclepro.2017.10.263

46. Christie P, Bennett NJ, Gray NJ, *et al*.: **Why people matter in ocean governance: Incorporating human dimensions into large-scale marine protected areas**. *Mar Policy* 2017, **84**:273-284, https://doi.org/10.1016/j.marpol.2017.08.002

47. • Mascarenhas A, Langemeyer J, Haase D, Borgström S, Andersson E: **Assessing the learning process in transdisciplinary research through a novel analytical approach**. *Ecol Soc* 2021, **26**:19, https://doi.org/10.5751/ES-12631-260419.
The authors put forward an analytical tool to assess learning processes of researchers and stakeholders participating in transdisciplinary processes, and present relevant insights from an initial application of the framework.

48. Borie M, Gustafsson KM, Obermeister N, Turnhout E, Bridgewater P: **Institutionalising reflexivity? Transformative learning and the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES)**. *Environ Sci Policy* 2020, **110**:71-76, https://doi.org/10.1016/j.envsci.2020.05.005

49. Borie M, Mahony M, Obermeister N, Hulme M: **Knowing like a global expert organization: comparative insights from the IPCC**

and IPBES. *Glob Environ Change* 2021, **68**:102261, https://doi.org/10.1016/j.gloenvcha.2021.102261

50. Iniesta-Arandia I, Quintas-Soriano C, García-Nieto AP, Hevia V, Díaz-Reviriego I, García-Llorente M, Mingorría S: **¿ Cómo pueden contribuir los estudios feministas y poscoloniales de la ciencia a la coproducción de conocimientos? Reflexiones sobre IPBES**. *Ecosistemas* 2020, **29**:1936, https://doi.org/10.7818/ECOS.1936

51. Báldi A, Palotás B: **How to diminish the geographical bias in IPBES and related science?** *Conserv Lett* 2021, **14**:e12786, https://doi.org/10.1111/conl.12786

52. Dendoncker N, Turkelboom F, Boeraeve F, *et al*.: **Integrating Ecosystem Services values for sustainability? Evidence from the Belgium Ecosystem Services community of practice**. *Ecosyst Serv* 2018, **31**:68-76, https://doi.org/10.1016/j.ecoser.2018.03.006

53. Pearce B, Adler C, Senn L, Krütli P, Stauffacher M, Pohl C: **Making the link between transdisciplinary learning and research**. In *Transdisciplinary Theory, Practice and Education*. Edited by Fam D, Neuhauser L, Gibbs P. Springer; 2018, , https://doi.org/10.1007/978-3-319-93743-4_12

54. Adler C, Hirsch Hadorn G, Breu T, Wiesmann U, Pohl C: **Conceptualizing the transfer of knowledge across cases in transdisciplinary research**. *Sustain Sci* 2018, **13**:179-190, https://doi.org/10.1007/s11625-017-0444-2

55. •• Wuelser G, Adler C, Breu T, Hirsch Hadorn G, Wiesmann U, Pohl C: **On which common ground to build? Transferable knowledge across cases in transdisciplinary sustainability research**. *Sustain Sci* 2021, **16**:1891-1905, https://doi.org/10.1007/s11625-021-01010-0.
In this paper, the authors empirically derive seven types of knowledge that can be considered transferable from a specific transdisciplinary case study to other cases.

56. Tuckey AJ, Harmáčková ZV, Peterson GD, Norström AV, Moore M-L, Olsson P, Lam DPM, Jiménez-Aceituno A: **What factors enable social-ecological transformative potential? The role of learning practices, empowerment, and networking**. *Ecology and Societ* (2) 2023, **28**:27, https://doi.org/10.5751/ES-14163-280227

57. • Schäfer M, Bergmann M, Theiler L: **Systematizing societal effects of transdisciplinary research**. *Res Eval* 2021, **30**:484-499, https://doi.org/10.1093/reseval/rvab019.
The paper introduces an empirically informed heuristic including the temporal and spatial dimension as well as possible forms of effects to allow researchers to consider and reflect societal effects of transdisciplinary research ex-ante, during the research process and ex-post.

58. • Lam DPM, Martín-López B, Wiek A, Bennett EM, Frantzeskaki N, Horcea-Milcu AI, Lang DJ: **Scaling the impact of sustainability initiatives: a typology of amplification processes**. *Urban Transform* 2020, **2**:3, https://doi.org/10.1186/s42854-020-00007-9.
The authors introduce a structured typology of amplification processes to scale and transfer impact of sustainability initiatives that can also be applied more generally for transdisciplinary processes.

59. Rogers EM: Diffusion of Innovations. 5th edn., Free Press; 2003.

60. Everard M, Reed MS, Kenter JO: **The ripple effect: institutionalising pro-environmental values to shift societal norms and behaviours**. *Ecosyst Serv* 2016, **21**:230-240, https://doi.org/10.1016/j.ecoser.2016.08.001

61. Loorbach D, Wittmayer J, Avelino F, von Wirth T, Frantzeskaki N: **Transformative innovation and translocal diffusion**. *Environ Innov Soc Transit* 2020, **35**:251-260, https://doi.org/10.1016/j.eist.2020.01.009

62. Balvanera P, Calderón-Contreras R, Castro AJ, Felipe-Lucia MR, Geijzendorffer IR, Jacobs S, Martín-López B, Arbieu U, Speranza CI, Locatelli B, Harguindeguy NP, Mercado IR, Spierenburg MJ, Vallet A, Lynes L, Gillson L: **Interconnected place-based social–ecological research can inform global sustainability**. *Curr Opin Environ Sustain* 2017, **29**:1-7.

63. Newig J, Jahn S, Lang DJ, Kahle J, Bergmann M: **Linking modes of research to their scientific and societal outcomes. Evidence from 81 sustainability-oriented research projects**. *Environ Sci Policy* 2019, **101**:147-155, https://doi.org/10.1016/j.envsci.2019.08.008

64. •• Chambers JM, Wyborn C, Ryan ME, *et al*.: **Six modes of co-production for sustainability**. *Nat Sustain* 2021, **4**:983-996, https://doi.org/10.1038/s41893-021-00755-x.
Based on the analysis of 32 initiatives, the authors identified six modes of co-production that can be used by researchers and societal actors to reflect on approaches for 'co-producing sustainability'.

65. • Pohl C, Hadorn GH: **Methodological challenges of transdisciplinary research**. *Nat Sci Soc* 2008, **16**:111-121.
Departing from four requirements of transdisciplinary research, the authors identify "transdisciplinary challenges and propose methods and tools to address them".

66. Brundiers K, Barth M, Cebrián G, Cohen M, Diaz L, Doucette-Remington S, *et al*.: **Key competencies in sustainability in higher education—toward an agreed-upon reference framework**. *Sustain Sci* 2021, **16**:13-29, https://doi.org/10.1007/s11625-020-00838-2 (S).

67. •• Barth M, Michelsen G: **Learning for change: an educational contribution to sustainability science**. *Sustain Sci* 2013, **8**:103-119, https://doi.org/10.1007/s11625-012-0181-5.
This paper presents core contributions educational science can make to the different levels of learning introduced in this article in order to foster sustainable development.

68. Sipos Y, Battisti B, Grimm K: **Achieving transformative sustainability learning: engaging head, hands and heart**. *Int J Sustain High Educ* 2008, **9**:68-86, https://doi.org/10.1108/14676370810842193

69. Dyball R, Brown VA, Keen M: **Towards sustainability: five strands of social learning**. In *Social Learning Towards a Sustainable World. Principles, Perspectives, and Praxis*. Edited by Wals (Hg.) Arjen EJ. Wageningen Academic Publishers; 2007:181-194.

70. Birdman J, Wiek A, Lang DJ: **Developing key competencies in sustainability through project-based learning in graduate sustainability programs**. *Int J Sustain High Educ* 2022, **23**:1139-1157.

71. Rotmans J, Loorbach D: **Transition management: reflexive governance of societal complexity through searching, learning and experimenting**. In *Managing the Transition to Renewable Energy: Theory and Practice from Local, Regional and Macro Perspectives*. Edited by van den Bergh JCJM, Bruinsma FR. Edward Elgar Publishing; 2008:15-46.

72. Olsson P, Bodin Ö, Folke C: **Building transformative capacity for ecosystem stewardship in social–ecological systems**. In *Adaptive Capacity and Environmental Governance*. Edited by Plummer R, Armitage DR. Springer; 2010:263-285.

73. Hebinck A, Diercks G, von Wirth T, *et al*.: **An actionable understanding of societal transitions: the X-curve framework**. *Sustain Sci* 2022, **17**:1009-1021, https://doi.org/10.1007/s11625-021-01084-w

74. • Singer-Brodowski M, Beecroft R, Parodi O: **Learning in real-world laboratories: a systematic impulse for discussion**. *GAIA-Ecol Perspect Sci Soc* 2018, **27**:23-27, https://doi.org/10.14512/gaia.27.S1.7.
Based on the discourse on Education for Sustainable Development the authors "differentiate three perspectives on the various learning processes occuring in" real-world labs and exemplify them with experiences in a concrete case.

75. • Bergmann M, Schäpke N, Marg O, Stelzer F, Lang DJ, Bossert M, Gantert M, Häußler E, Marquardt E, Piontek FM, *et al*.: **Transdisciplinary sustainability research in real-world labs: success factors and methods for change**. *Sustain Sci* 2021, **16**:541-564, https://doi.org/10.1007/s11625-020-00886-8.
The paper presents evidence-based insights from the accompanying research of 14 real-world labs with regard to success factors and methods of change.