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Transdisciplinary complexity science: deepening system understanding for sustainability

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The complex and contextual nature of sustainability challenges demands an approach that integrates quantitative complexity science with transdisciplinary approaches to create an integrated understanding of system change. We present a systematic literature analysis from an emerging field we term Transdisciplinary Complexity Science for Sustainability and derive best practices for how this research approach can foster learning and action for sustainability. Based on our analyses, we identify key areas for future research and provide concrete recommendations for carrying out Transdisciplinary Complexity Science for Sustainability.

Introduction

Achieving sustainability requires reorganising our societal systems so that they meet the needs of the present without compromising the ability of future generations to meet theirs (Brundtland, 1987). The complexity of achieving sustainability is manifest in the breadth and interdependency of the Sustainable Development Goals (SDGs) (Pradhan et al., 2017). System understanding is thus key to enabling action towards sustainability. Complexity science and transdisciplinary science are well-developed approaches that create insight into how complex systems function and are experienced, respectively, with transdisciplinary science often focused on translating insights into action. By systematically analysing literature that combines complexity science and transdisciplinary methods, we aim to understand how their integration may foster system understanding that can be translated into action towards sustainable systems.

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Complexity science is a set of theories and methods for developing mechanistic understanding of complex phenomena across social and natural systems and has shown promise in helping to realise the SDGs (Mitchell and Toroczkai, 2010; Omodei et al., 2022). In this paper, we focus on quantitative complexity methods such as system dynamics modelling, network analysis, and agent-based modelling, each of which has greatly improved our understanding of the structure and dynamics of systems in the last decades (Domenico and Sayama, 2019). For example, system dynamics modelling has revealed non-linear tipping points in complex biophysical systems (Rietkerk et al., 2021; Schlüter et al., 2019). Network analysis has revealed the structures of social and natural systems and how these structures constrain system change (Bodin et al., 2019). Agent-based modelling has allowed us to understand how complex adaptive systems, such as coupled human-nature systems, emerge through self-organisation processes (An, 2012). In doing so, it has revealed how large-scale patterns like bird flocks or economic markets emerge from small-scale interactions among adaptive individuals (Dermody et al., 2011; Farmer and Foley, 2009).

Transdisciplinary science is an approach that aims to understand how systems are experienced by involving academic and non-academic stakeholders who collaboratively co-produce knowledge to address a challenge (Funtowicz and Ravetz, 1993; Lang et al., 2012; Pohl et al., 2017). This collaboration reshapes the knowledge of all stakeholders, improves their system understanding, improves research legitimacy, and increases the likelihood that the research findings will address the given sustainability challenge in a just way (Aminpour et al., 2020; Horcea-Milcu et al., 2022; Morton et al., 2015; Norström et al., 2020). Transdisciplinary science has been demonstrated to address issues of (in)justice around sustainability by providing a platform to integrate marginalised voices within the research process (Huang and London, 2016; Norström et al., 2020). A key focus has been on how the transdisciplinary learning process itself facilitates co-learning and knowledge co-production among participants (Knickel et al., 2019; Norström et al., 2020). An idealised transdisciplinary research process engages stakeholders with the aim of empowerment and in all study phases, from initiation, problem identification, to knowledge production, and knowledge reintegration with the aim of taking joint action (Horcea-Milcu et al., 2022; Lang et al., 2012). Achieving stakeholder participation in all phases and understanding the role of the scientific experts with policymakers is, nevertheless, often challenging (Brandt et al., 2013; van Bruggen et al., 2019).

We define Transdisciplinary Complexity Science for Sustainability (TCSS) as an approach that engages academic and non-academic stakeholders in the application of quantitative methods from complexity science to take action for complex sustainability issues (Fig. 1). TCSS opens the possibility for deepening system understanding by integrating mechanistic and experiential understandings of complex systems. TCSS can improve the societal relevance of complexity research by helping align complexity research with sustainability challenges in a given context. Equally, engaging stakeholders in complexity science can foster system learning and provide stakeholders with system knowledge to create action for sustainability.

In order to identify best practices for an emerging field of TCS for sustainability, we carry out a systematic literature review focusing on previous academic articles that combine quantitative complexity science methods with transdisciplinary approaches to address sustainability. From our analysis, we draw important lessons about how complexity science can be best integrated into transdisciplinary research and what is needed to allow this emerging field to grow and contribute to deepening our understanding of sustainability.

Methods

The data collection process of this systematic literature review was guided by the "Preferred Reporting Items for Systematic

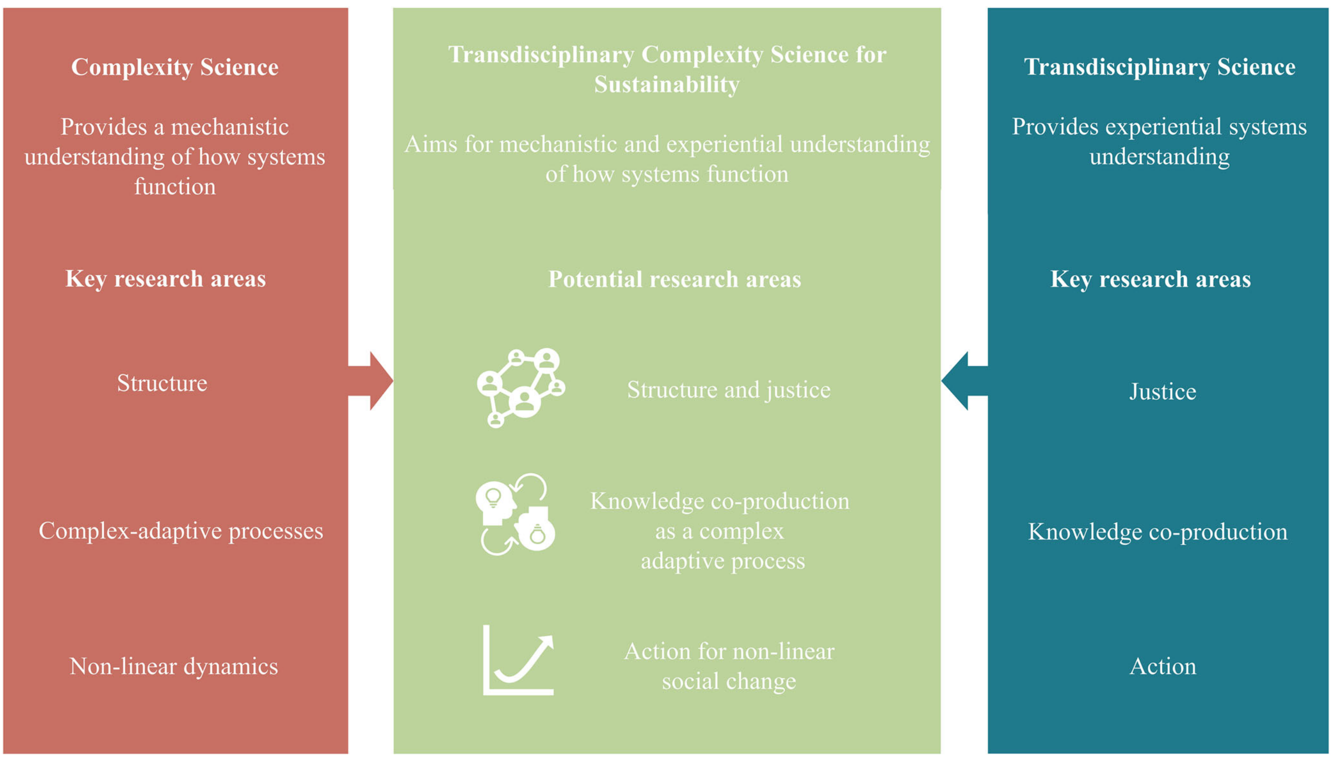

Fig. 1 Conceptual framework for Transdisciplinary Complexity Science for Sustainability. Integrating knowledge from complexity science and transdisciplinary science can open up new knowledge on themes such as structure and injustice, co-learning as a complex adaptive process, and action for non-linear social change.

Table 1 The applied search strategy.

Item	Description
Research question	How has previous research on sustainability combined transdisciplinary and quantitative complexity science methodologies?
Search terms for complexity science	Complexity science*, differential equat*, complex network*, discrete event model*, system dynamic*, dynamic* system, agent-based*, graph theor*, cellular aut*, multi-agent*, game theor*, informat* theo*, fixed point*, mathematical model*, computational model*, dynamic* model, stochastic process*, statistical mechanic*, statistical physic*, evolution* dynamic*, complex* model, jacobian, bifurcati*, chao*, non-equilibrium, random walk*, *stability analysis*, swarm optimi*, colony optimi*, *network analys*, *network science, network motif*, *random graph*, reaction diffusion*, *ising model*, genetic algorithm*, information theor*, logistic map, markov chain, information theor*, maximum likel?hood*, entrop*
Search terms for transdisciplinary science	Transdiscipl*, knowledge co-product*, knowledge co-creat*, knowledge co-design*, knowledge co-construct*, knowledge co-disseminat*, co-learn*, post-normal*, community-engag*, community-cent*, community-focus*, participat*
Search terms for sustainability	Sustainab*
Search within	Article title, Abstract, Keywords
Inclusion criteria	Transdisciplinarity: applied a transdisciplinary approach Complexity: applied a complexity science method Sustainability: studied an SDG Type: peer-reviewed original scientific articles written in English

Reviews and Meta-Analyses" (PRISMA) framework (Appendix A) (Page et al., 2021). To answer the research question *How has previous research on sustainability combined transdisciplinary and quantitative complexity science methodologies?*, a search string (Appendix B) was devised with all co-authors to yield papers that combine transdisciplinary and complexity science in a sustainability context (Table 1). This search string was refined with a scoping exercise and iterative discussions among the co-authors (LdJ, BJD, EO, IL, ID, SZ, CW, MB, AvB, and KB) to ensure the inclusion of relevant search terms.

It should be noted that other articles that meet the general scope may have been missed with our search string, as they don't match the specific search terms in Table 1. For example, research on social-ecological systems has pioneered our understanding of complex systems in relation to sustainability challenges. However, those papers often emphasise system resilience and use that term, rather than the term sustainability (e.g., Levin, 1998; Preiser et al., 2018; Schlüter et al., 2019). The potential of modelling has long been valued in social-ecological systems science, and there is a growing recognition of the need to further integrate transdisciplinary approaches into social-ecological systems modelling (Folke et al., 2016; Horcea-Milcu et al., 2020; Schlüter et al., 2019; Steger et al., 2021). We are aware of these overlaps and reference relevant literature in our discussion. However, the scope of our paper is limited to papers that use the term sustainability explicitly in the title, abstract, or keywords.

The search string was applied to the Scopus database on July 6th, 2022, and returned 912 articles. In line with the Cochrane Handbook for Systematic Reviews of Interventions, the abstracts of the articles were screened for eligibility. Articles that did not meet the inclusion criteria were excluded. Only the remaining articles that passed the initial screening were subjected to a full-text assessment.

The abstracts were screened for eligibility on three successive levels. First, co-authors with expertise in complexity science (BJD, EO, MB, CW, AvB) screened the abstracts and excluded articles that did not employ a complexity methodology (512 excluded). Second, one of the authors (LdJ) excluded articles that did not employ a transdisciplinary approach. Hence, all articles that discuss transdisciplinary approaches but do not apply them were excluded (323 excluded). The screening of abstracts on transdisciplinarity was cross-checked by another co-author (AvB). Third, articles that did not relate to any of the Sustainable Development Goals (SDGs) were excluded (20 articles).

The final set of articles was coded with attention to the SDGs covered by the research, the complexity method(s) applied, and the phase of transdisciplinary research in which the methods were applied. In all cases, multiple entries were possible if an article used multiple complexity methods and addressed multiple phases of transdisciplinary research or multiple SDGs.

The transdisciplinary phase was deductively coded, ranging from initiation to implementation, using the joint framework of Lang et al. (2012) and Horcea-Milcu et al. (2022). This framework was selected for its systematic approach to distinguish between four research phases in which a transdisciplinary approach can be applied. Co-authors with expertise in transdisciplinary science (SZ, ID, BV, AGM, AvB, CAP) cross-checked the coding and resolved any inconsistencies in categorising the transdisciplinary phases through discussion.

The complexity-associated method of each article was inductively coded by two co-authors (BJD, LdJ) and cross-checked by a subset of co-authors with complexity science expertise (EO, MB, CW, AvB). The resulting codes were grouped into complexity methods based on similarities in their conceptual foundations. Where there was a disagreement, the coding was discussed and the disagreement was resolved by two co-authors (LdJ, BJD).

Finally, the most relevant SDGs addressed in the papers were deductively coded by one of the authors (LdJ). The SDGs served as a framework to differentiate between various types of sustainability research, highlighting where TCSS research has been most widely applied and highlighting gaps in its application across different sustainability challenges.

Transdisciplinary complexity science in past research

Our systematic search returned 912 articles, of which 56 met the inclusion criteria (see Appendix A for PRISMA flowchart of the screening process). TCSS was most often applied to address SDG 15 ($N = 21$), focused on promoting the sustainable management of terrestrial ecosystems (Fig. 2).

The main complexity methods applied in the identified literature were system dynamics modelling ($N = 26$), agent-based modelling ($N = 19$), and network analysis ($N = 11$), with some papers combining the latter two approaches ($N = 2$) (Giordano et al., 2021; Hennessy et al., 2020). System dynamics modelling was generally used to explore complex biophysical processes by implementing knowledge of stakeholders living within and/or managing a local ecosystem. This process often took place in

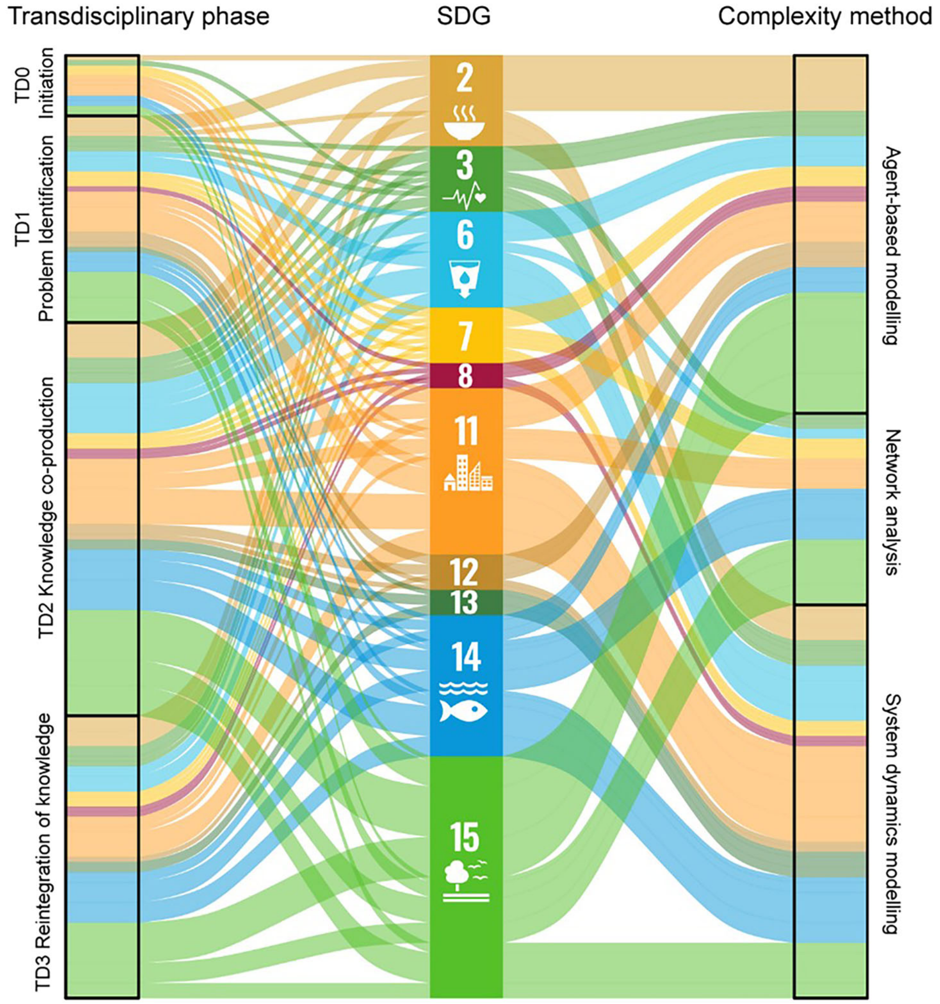

Fig. 2 Alluvial diagram showing the relative distribution of papers across SDGs, transdisciplinary research phases, and complexity science methods.

group model-building workshops where stakeholders co-developed system maps, such as causal loop diagrams, together with researchers. The researchers formalised these maps into system dynamics models with additional empirical data and shared the outcomes in follow-up workshops (Alizadeh et al., 2022; Beall et al., 2011; Chen et al., 2014; Inam et al., 2017; Kumar et al., 2016; Richardson et al., 2021; Schmitt Olabisi et al., 2010; Shi et al., 2019; Videira et al., 2009; Weeks et al., 2020).

Agent-based modelling, which represents systems through the behaviour and interactions of individual actors, was mostly applied to understanding social processes, such as the effect of decision-making on a local environmental problem (Barnaud et al., 2008; Campo et al., 2009; Castella et al., 2007; Catarino et al., 2021; Delmotte et al., 2016; Dieguez Cameroni et al., 2014; Giordano et al., 2021; Le Page et al., 2015; Montalto et al., 2013; Rojas et al., 2022; Ruankaew et al., 2010; Smajgl, 2010; Smetschka and Gaube, 2020; Steger et al., 2022). Agent-based modelling was often performed using the companion modelling approach (Etienne, 2013) to cultivate a shared understanding of multi-stakeholder decision-making processes (van Bruggen et al., 2019).

Network analysis was often combined with participatory methodologies, such as workshops and participatory network mapping, but with a focus on system structure rather than dynamics (Bowditch et al., 2020; Boyle et al., 2021; Chuvileva et al., 2017; Cottafava and Corazza, 2021; Delgado-Serrano et al., 2015; Fynn et al., 2021; Gerhardinger et al., 2022; Kratzer, 2018; Starkl et al., 2013; Tringali et al., 2017).

In terms of the phase of the transdisciplinary research process in which complexity research is applied, a limited number of articles reported that stakeholders participated in preparatory activities prior to the initiation of research, such as stakeholder selection or expectation management (TD0, $N = 6$). In roughly half of the papers, the research engaged stakeholders in problem identification (TD1, $N = 24$). Knowledge co-production was present in all papers (TD2, $N = 56$), in the form of collaboratively developing agent-based models, system dynamics models, or constructing networks with stakeholders. Many papers reintegrated the co-produced knowledge (TD3, $N = 38$), for instance, by collaboratively developing scenarios and pathways to be explored in the models, or by providing stakeholders with co-created tools that facilitate decision-making processes.

Some SDGs were well represented (SDG 2/Zero hunger, 6/Clean water and sanitation, 11/Sustainable cities and communities, 14/Life below water, 15/Life on land), while others were underrepresented (SDG 3/Good health and wellbeing, 7/Affordable and clean energy, 8/Decent work and economic growth, 12/Responsible production and consumption, and 13/Climate action) or not studied at all (SDG 1/No poverty, 5/Gender equality, 9/Industry, innovation, and infrastructure, 10/Reduced inequalities, 16/Peace, justice, and strong institutions, and 17/Partnership for the goals). Agent-based modelling was frequently applied to study SDG 15 (Life on land, $N = 20$) and SDG 2 (Zero hunger, $N = 8$), while system dynamics modelling was often used to study SDG 11 (Sustainable cities and communities, $N = 13$), SDG 6 (Clean water and sanitation, $N = 10$), and SDG 14 (Life below water, $N = 10$). These approaches were most often used during the knowledge co-production (TD2) and reintegration of knowledge (TD3) phases of transdisciplinary research.

Deepening system understanding for sustainability

The integration of complexity and transdisciplinary methods was found to improve stakeholders' learning of system complexity in certain cases. For example, Martínez-Fernández et al. (2021) and Richardson et al. (2021) reported that stakeholders learned about non-linear ecosystem processes through the application of system dynamics modelling. In Campo et al. (2009), stakeholders were reported to better understand emergent processes through the application of companion modelling within an agent-based model. Network analysis was also reported to help stakeholders understand how systemic factors like governance structures affected their ability to make sustainable changes (Delgado-Serrano et al., 2015). Formal evaluation of the advancement in system understanding was rarely done; nevertheless, Lee et al. (2021) measured learning outcomes of a marine ecosystem game with a survey, test, interviews, and participant observations and found that the collaboration of multiple teams improved participants' behavioural engagement and learning achievements.

Crucially, stakeholders reported that being included in the co-development of the research increased their trust in the quantitative models ($N = 7$) (Campo et al., 2009; Dieguez Cameroni et al., 2014; Gourmelon et al., 2013; Le Page et al., 2015; Rojas et al., 2022; Shi et al., 2019; Smetschka and Gaube, 2020). Equally, the focus of many articles on representing stakeholder knowledge was found to improve the relevance of complexity methods ($N = 7$) (González-Rosell et al., 2020; Gourmelon et al., 2013; Kumar et al., 2016; Martínez-Fernández et al., 2021; Olivar-Tost et al., 2020; Tringali et al., 2017). For example, Olivar-Tost et al. (2020) used a transdisciplinary approach to derive values of the relative importance the community gave to different variable classes within a system dynamic model for green project prioritisation.

Systematic empirical validation of the efficacy of TCSS in enabling action for sustainability was lacking. Nonetheless, support for the efficacy is provided across the reviewed studies. In Chen et al. (2014), co-developing a system dynamics model of a wetland system in Taiwan improved stakeholder understanding of dynamics in the system and was shown to empower stakeholders to sustainably manage the wetland system. In Austria, farmers adopted sustainable agricultural practices after participating in a research project where an agent-based model was co-developed to explore the influence of farmer decision-making on the local environment (Smetschka and Gaube, 2020). Another example is presented by Shi et al. (2019), where stakeholders co-developed a system dynamics model of urban traffic restriction policies in China. Citizens were involved in all phases of the research process and given a voice in decision-making procedures, which was reported to increase the social support for urban planning projects. The proposed urban traffic restriction policy was found to reduce local traffic and environmental problems.

Practical challenges for transdisciplinary complexity science

Based on our analyses, we highlight some practical challenges for TCSS related to (1) introducing complexity science methods to non-academic stakeholders, (2) maintaining participation in model development, (3) integrating a diversity of stakeholder views within models, and (4) the validation of models. But these challenges also provide opportunities to advance this emerging field in productive directions.

Firstly, introducing complexity science methods to non-academic stakeholders can be challenging due to the specific knowledge type required for understanding and applying complexity science methods. Addressing this challenge requires strong facilitation skills that enable the translation of scientific methods to non-academic language. Community-based system dynamics is a tool that facilitates participatory system dynamics modelling, where a community facilitator is invited to act as a bridge between the scientific and non-scientific stakeholders (Hovmand, 2014; Kumar et al., 2016). For example, in Kumar et al. (2016), employees of a local partner agency that have been working with the local community for many years were invited as community facilitators in the research project. The community facilitators introduced participants to the research team and project and helped to communicate the participants' perceptions of the sustainability issue to the research team.

A second challenge for TCSS is that quantitative model development often takes time, and thus can be impacted by changes in participants across phases of the transdisciplinary process. Castella et al. (2007) highlight that a declining participation rate and changing group composition threatened the modelling process as it led to uncertainties about what had been discussed in previous workshops. Here, providing participants with a summary of previous workshop results proved to be an effective strategy. This dependence on stakeholder participation emphasises the importance of an inclusive and diverse participatory process around defining a conceptual framework in phase 1 of the transdisciplinary process, which provides a representative and legitimate framework for model development, despite changing personnel (Steger et al., 2021).

Thirdly, transdisciplinary approaches face the challenge of building a shared understanding of a system when often stakeholders hold diverse and often conflicting perspectives. This challenge may be amplified when integrating transdisciplinary approaches with complexity science, as quantitative models demand simplifications to capture key aspects of complex systems relevant to the research question. Group-based approaches such as group model building or companion modelling provide well-developed frameworks for integrating diverse knowledge and perspectives within the transdisciplinary process. However, often the research goal may require retaining diverse perspectives rather than integrating them, and as such, group processes may not be the best approach (Turnhout et al., 2020). Equally, group processes are sensitive to groupthink and power dynamics, which can lead to premature convergence on a suboptimal solution (Fiore et al., 2001; van den Broek, 2018). Here, complexity methods such as network analysis or agent-based modelling combined with individual interviews, role-playing games, focus groups, or surveys can be powerful ways to retain diverse and marginal knowledge and perspectives within the transdisciplinary model-building process.

Finally, while models are conventionally validated by comparing simulated and observed data, this approach can be difficult to apply to models that were produced in a transdisciplinary setting. For Barnaud et al. (2008), validation was described as a process to build stakeholder confidence in the model in the sense that it accurately represents stakeholder perspectives of the system. This involved actively engaging stakeholders in the early phases of the transdisciplinary process, such as soliciting their feedback on whether any key dynamics were absent from the model. In this way, validation becomes an iterative process incorporating model design and model output, and makes the final model a more accurate representation of reality, allowing more effective action.

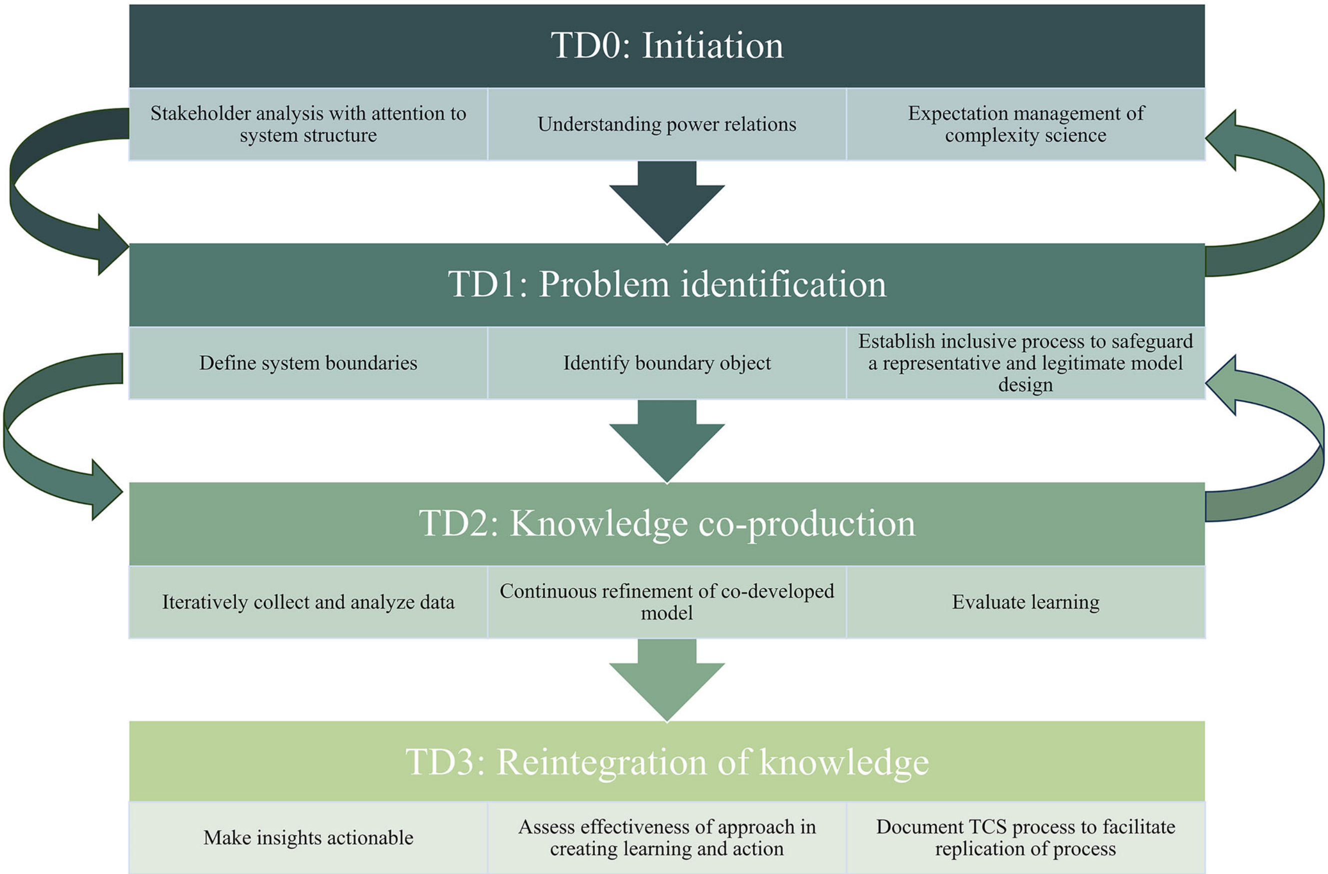

Fig. 3 The four phases of the Transdisciplinary Complexity Science for Sustainability process. The first 3 phases are reflexive and iterative.

Recommendations for developing transdisciplinary complexity science for sustainability

We recommend the following steps per study phase to further develop TCSS (Fig. 3). While in-depth instructions are beyond the scope of this paper, these suggestions are starting points to further the integration of transdisciplinary and complexity science approaches, both in empirical applications and methodological work to advance the field.

TD0 phase: initiation. The initiation phase of an ideal TCSS process should begin by managing expectations around the complexity science approach that will be used, performing a stakeholder analysis with attention to stakeholder diversity and an analysis of power asymmetries (Horcea-Milcu et al., 2022). Horcea-Milcu et al. (2022) emphasise the importance of understanding the case context and the premises for coming together in phase 0. In this step of a TCSS process, it is important to foster an open dialogue about what complexity models can and cannot do with relation to the context in order to manage stakeholder expectations (van den Broek et al., 2020). This is especially important when introducing complexity science methods, which are often unfamiliar to stakeholders involved (van Bruggen et al., 2019).

Even at this early stage in the research process, it may be useful to introduce complexity methods such as network analysis to safeguard the inclusion of diverse and peripheral stakeholders within the stakeholder selection process (Hubacek et al., 2006; Kirchherr and Charles, 2018; Paletto et al., 2015). As with any transdisciplinary process, ensuring a diverse group of participants is essential to gain a holistic system understanding and a legitimate process. But this is particularly relevant in the early phase of TCSS, as model design decisions are not easily modified; thus, having a representative group of stakeholders from the beginning lowers the risk of neglecting crucial system components in the model design (Steger et al., 2021). Finally, power relations among participants can be better understood by a joint mapping of the values, perspectives, and interests of participants (Turnhout et al., 2020). This can inform the design of subsequent transdisciplinary processes with attention to power asymmetries.

TD1 phase: problem identification. The main aim of the TD1 phase is to collaboratively identify and frame the real-world problem and build a research team. In this phase, stakeholder engagement can be improved by translating the real-world challenge into a boundary object (Lang et al., 2012). Boundary objects are artifacts that can be interpreted differently by stakeholders while providing a point for collaboration (Star and Griesemer, 1989). Complexity models can be employed as boundary objects, as demonstrated in Steger et al. (2022), where stakeholders interpreted an agent-based model of local grasslands in accordance with their values and goals for conservation of the area. In creating a boundary object, the complexity method should be adapted to the problem, and not the other way around (Barnaud et al., 2013). Formalising the problem as a model also helps with defining the boundaries of the system to be studied and encourages stakeholders to think about what are key aspects that should be included in the model and what can be treated as external to the model (Purwanto et al., 2019). It is key to allocate sufficient time to the TD1 phase in order to enable inclusive processes that allow for diverse stakeholder participation.

Inclusive participation of stakeholders benefits the representativeness and legitimacy of the model design (Hansson and Polk, 2018).

TD2 phase: knowledge co-production. Central to the TD2 phase is an iterative process of collecting and analysing data using transdisciplinary complexity approaches that foster co-learning. It is important that equal emphasis is placed on both sharing insights from the model and gathering insights from stakeholders to improve the model. Existing approaches, such as group model building (Vennix et al., 1996) or companion modelling (Etienne, 2013), can be applied to guide the process of co-developing a model. In Videira et al. (2009), knowledge co-production was initiated by inviting stakeholders to share their understanding of the sustainability issue, for example, in a causal loop diagram. This framework then served as the foundation to identify relevant variables and dynamics to be incorporated in the model. Once the research team specified the model with scientific data, stakeholders evaluated and improved the model, ensuring that the model maintains practical relevance. This iterative process allows for continuous refinement of the model. Ideally, the co-learning that occurs should be evaluated at each step, but to the best of our knowledge, consistent frameworks for doing so are not yet available (see below).

Besides evaluating learning outcomes, the knowledge co-production phase offers the space for reflexivity. Academic and non-academic stakeholders can critically evaluate how the selected method or approach and underlying values or assumptions influence the research process. A reflexive approach to knowledge co-production in TCSS implies an iterative process of joint experimentation with methodologies and making adjustments where needed (Popa et al., 2015). The outcome, therefore, may require revisiting phases 0 and 1.

TD3 phase: reintegration of knowledge. Successfully engaging stakeholders in each phase of the research enables learning about system structure and dynamics, as well as contextual and subjective perceptions of how the system is experienced and what stakeholders would view as indicators for monitoring system improvement. The TD3 phase focuses on reintegrating the insights of the research and making them actionable. Exploring the influence of various solutions on the sustainability challenge should provide stakeholders with a basis for action, which includes quantitative data.

Alongside evaluating concrete outcomes toward sustainability challenges, it is important to evaluate the perceived learning and empowerment that have occurred among project participants at this stage. Therefore, we recommend future work to develop and apply assessment frameworks for specifically evaluating the effectiveness of combining complexity and transdisciplinary methods that focus on facilitating co-learning and action for sustainability. Existing frameworks that evaluate the contribution of transdisciplinary research to address sustainability issues can be adapted to also incorporate these dimensions (Plummer et al., 2022).

It will also be important to develop frameworks for describing the transdisciplinary process in TCSS studies to ensure future research is transparent, the method is reproducible, and that outcomes that claim action for sustainability can be assessed based on the process described. In this case, frameworks used from complexity science, such as the ODD protocol from agent-based modelling (Grimm et al., 2006, 2010), can be adapted to explain and justify how the transdisciplinary process informed model design.

Conclusion

To achieve action towards sustainability, it is crucial to foster transdisciplinary learning in complex systems. Successfully engaging stakeholders in each phase of the research enables learning about system structure and dynamics as well as contextual and subjective perceptions of how the system is experienced and what stakeholders would view as indicators for system improvement. The body of research analysed here provides direction and inspiration for how this can be done.

There is great potential to exploit the benefits of TCSS in future studies, as there is a limited body of research that has integrated both approaches, and the SDGs have been unevenly addressed. We believe that TCSS can be a powerful way to foster system understanding and action for sustainability in these areas. A support base for action towards sustainability can be mobilised with tools that represent both the complexity and stakeholders' experience and understanding of systems.

In particular, future research can target SDGs that are currently underrepresented in TCSS studies. For example, SDG3 (Good health and well-being) can be addressed with agent-based or system dynamics models of disease spread or healthcare interventions. Integrating transdisciplinary approaches by engaging healthcare practitioners and communities ensures that these models account for relevant behavioural factors and improve intervention uptake. Similarly, SDG 5 (Gender inequalities) can benefit from network analysis combined with transdisciplinary approaches to reveal gendered power structures in social networks. This approach helps identify gender differences in access to opportunities and resources while ensuring that the research amplifies the perspectives of women and actively supports their empowerment.

Moreover, the integration of transdisciplinary processes is less prevalent in the initiation and problem-formulation phases of the research. To stimulate transdisciplinary complexity research further, sustainability journals and funding bodies should encourage authors to document how co-learning and action was facilitated within the research, and ideally, evaluate to what extent it was achieved. This allows the wider research community to reproduce research, and to learn which approaches show promise in different contexts.

Data availability

The data is publicly available at Zenodo: https://doi.org/10.5281/zenodo.10807910.

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Author contributions

BJD, ID, ND, AGM, EO, IL, CBMK, CAP, MB, MS, SZ, MBau, AvB, and CW conceived the idea within a workshop setting. LdJ and BJD wrote the manuscript with contributions from ID, ND, AGM, IL, CBMK, MB, MS, SZ, MBau, CW, HD, AvB, and KB. Search string was developed by LdJ, BJD, EO, IL, ID, SZ, CW, MBau, AvB, and KB. Systematic literature review was carried out by LdJ with support from ID, AGM, MBau, EO, CAP, SZ, BJD, and AvB.

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The authors declare no competing interests.

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