Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

From transdisciplinary projects to platforms: expanding capacity and impact of land systems knowledge and decision making

Jonathan Morgan Grove[1,2] and Steward TA Pickett[1,2]

Land system science can inform decision making to address societally important issues, including food, energy, and water security, livelihoods and lifestyles, biodiversity loss, and climate change. There is growing experience among scientists and practitioners with land systems as a transdisciplinary science. Most often, this experience has accumulated through short-term projects. However, there is a need for durable, long-term land system science platforms to address diverse types of complex, wicked problems, from immediate crises and emergencies over days and weeks; to sudden events over months and years; to extensive, pervasive, and subtle changes occurring over decades. In this paper, we offer a strategic framing of the issues and features for transdisciplinary land system science platforms that can be adapted and applied to local conditions.

Addresses
[1] Baltimore Field Station, USDA Forest Service, 5523 Research Park Drive, Suite 350, Baltimore, MD, 21228, USA
[2] Cary Institute, Cary Institute of Ecosystem Studies, Box AB, Millbrook, NY, 12545, USA

Corresponding author: Grove, Jonathan Morgan (morgan.grove@usda.gov)

Current Opinion in Environmental Sustainability 2019, **38**:7–13

This review comes from a themed issue on **Sustainability governance and transformation**

Edited by **Rinku Roy Chowdhury**, **Darla K Munroe** and **Ariane de Bremond**

For a complete overview see the Issue and the Editorial

Available online 6th May 2019

https://doi.org/10.1016/j.cosust.2019.04.001

1877-3435/Published by Elsevier B.V.

Introduction

Land use change is a key process affecting societies' ability to meet sustainability and resiliency challenges at multiple scales. Although land use change may seem primarily to be about temporal patterns of how people structure and exploit the terrestrial surface of the Earth, understanding land use change, in fact, requires knowing the motivations, behaviors, and systems with which people interact with terrestrial ecosystems. These interactions have diverse effects on societally important issues including food, energy, and water security, livelihoods and lifestyles, biodiversity loss, and climate change [1]. Land use change can be conceived of as complex, adaptive social-ecological systems [2] with dynamic interactions among different types of actors, practices, and technologies. The feedback between land use and environmental dynamics are important aspects of the interaction of people and ecosystems [3,4].

Land system science addresses these dynamic interactions by monitoring and describing patterns of land-cover change, explaining drivers of land-use change, and understanding interactions between land-cover and land-use change. Land system science produces data and knowledge in several ways, including deductive approaches, abductive reasoning, and syntheses of existing knowledge [1]. Land system science often employs these approaches in collaboration with decision makers [5,6] to identify questions, collect data, interpret findings, and co-produce actionable science. Such co-production approaches are seen as fundamental to transdisciplinary science [7]. In addition to co-production, transdisciplinary science combines interdisciplinary approaches, working in teams [8], and the production of actionable science [9,10].

Scientists 'and practitioners' experience with transdisciplinary science for land systems is growing [5,6,11]. Short-term projects have generated valuable experience and training programs have been developed for current professionals and students [12,13]. Major funding sources at regional, national, and international levels are expanding their portfolios to support transdisciplinary land system science [14,15]. An important question remains, however: what is the best way to create durable networks of people, organizations, and data to make the transition from individual, short-term projects to persistent, long-term platforms for transdisciplinary land system science. This question is important because too often scientists and practitioners find the duration of project funding to be inadequate. Often, just as a transdisciplinary project begins to work well, the project funding ends. The team might try to find new funding for their existing project. They might pursue new funding opportunities for new projects. In either case, researchers and practitioners are faced quite frequently with significant 'start-up' costs to establish new transdisciplinary projects and organizing new teams. This is frustrating, inefficient, and often ineffective for scientists and practitioners alike. In this paper, we propose that it is important to strategize the transition from short-term projects to long-term platforms, which includes features and infrastructure to support on-going multi-sectoral and transdisciplinary collaborations to address and adapt to short-term crises and long-lasting wicked problems in land systems.

While this transition may avoid the feeling and costs of 'déjà vu all over again' from starting a new, similar to the last, transdisciplinary project; we also propose that transdisciplinary land system science platforms can inform co-produced sustainability pathways to more resilient socio-ecological systems in ways that cannot be achieved on a project by project basis.

This paper does not attempt to offer detailed prescriptions for how to build long-term, transdisciplinary land science platforms. Rather, it offers a strategic framing of the issues and features for such a platform. In essence, we identify key features to keep in mind in developing durable platforms for transdisciplinary research and problem solving. Thus, this paper identifies (1) what are some of the challenges to be solved; (2) what are some existing building blocks; (3) what are some of the desired outcomes; and (4) what strategic features might be installed to take advantage of existing building blocks to achieve the desired outcomes (Figure 1). Our intent is that this framing and identification of features can be adapted and applied to fit the local conditions that scientists and practitioners face in their own context.

Challenges

It is increasingly clear that understanding and acting upon land systems are ineffective with limited datasets and simplified models of land-use and land-cover change [16]. Land system changes are characterized by complex interactions and multi-causality at multiple scales [1]. Further, land system science needs to address the simultaneity of land systems, which are "a biophysical entity, a territory, a commodity, a habitat for nonhuman species, a resource for productive activities, and a buffer for absorbing pollutants. [These systems are] allocated, regulated, and administrated by various laws, norms, and rules [and] a source of meaning and sense of place, a landscape component, and symbolically loaded [1:53]."

Land systems represent several types of problems for decision makers. Land systems are often characterized by wicked problems. Wicked problems are composed of complex systems and interacting and inter-dependent parts [17]. Actors often hold diverse and conflicting values and perspectives. Solutions are often uncertain and suboptimal [18,19]. These wicked problems also have different temporal dimensions. While events over months and years; to extensive, pervasive, and subtle changes occurring over decades may be the most familiar kinds of wicked problems [20], there is a growing need for real-time responses to unfolding crises and emergencies. Understanding such emergencies helps motivate transdisciplinary approaches [21].

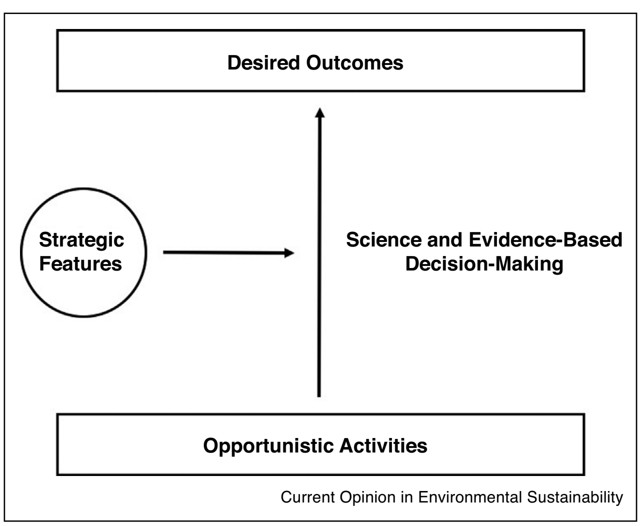
When practitioners seek to use science and evidence-based decision making to address these wicked problems, they are confronted with a variety of scientific challenges. There may be diverse scientific perspectives on how the system works, the nature of its past, and the shape of its likely futures. There may be incomplete data, uncertain knowledge, or varying levels of confidence in the data and knowledge. Analytical models may not exist or be insufficient to deal with the complexity of the problem. Finally, there may not be resources for monitoring and evaluating the long-terms impacts of interventions.

Land system scientists have their own challenges. On one hand, there is limited but growing experience and training with transdisciplinary projects: how to do interdisciplinary, team-based, and actionable science. However, there are few models for how to build long-term and durable platforms that are based on reliable and long-term institutional support and budget, and thus have sufficient time to develop important dimensions [22–25]. These factors are critical for long-term, transdisciplinary platforms to refine their functions, build and maintain effective intellectual networks, develop social cohesion, and establish effective data systems [22–25].

From projects to platforms

The expansion from short-term land system projects to long-term platforms has three main elements: (1) existing opportunistic activities; (2) desired outcomes; and (3) strategic features (Figure 1). A critical insight from this

Figure 1



Key elements for the expansion from short-term, transdisciplinary land system science projects to long-term platforms.

diagram is to recognize that in any locale there are numerous, existing opportunistic activities related to land system science and decision making. Decision makers are likely to have support from trained technical staff, consultants and firms, professional organizations, or regional and national agencies. They will also have their own administrative data. Decision making processes may be subject to public input and review. There may be intermittent interactions with academics and researchers.

Academics and scientists conduct research with support from within their institutions and from external sources. These research activities are sometimes conducted under the auspices of a cross-disciplinary or synthetic university initiative or via a course that brings together students or faculty from various perspectives, and through course projects. However, most sponsored science projects tend to be short-term and non-cumulative. Data are collected, often for a single use and over a short period of time. There may be intermittent interactions with decision makers.

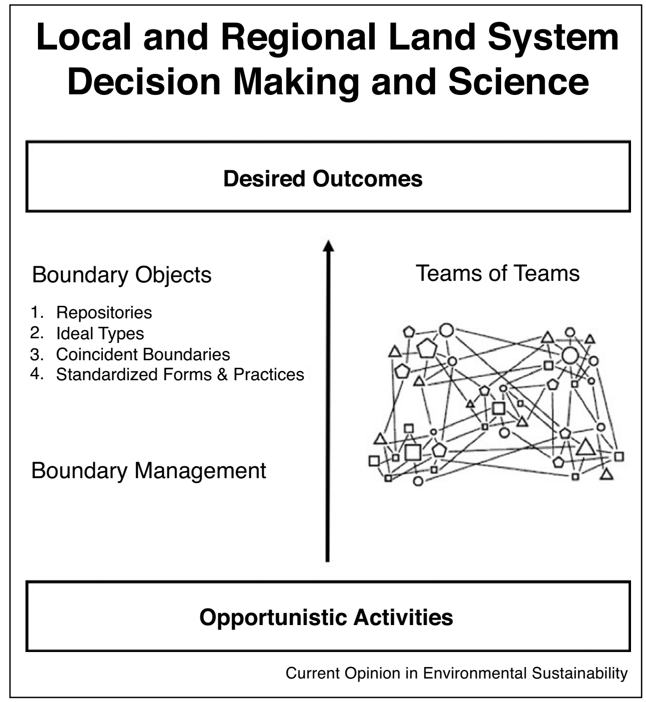
A set of desired outcomes is the second element of the framework. When practitioners adopt science and evidence-based decision making, they may have several concerns. Decision makers may seek to reduce the costs and increase the timeliness of data, while accessing data from multiple disciplines and multiple sectors. They may need continuity and durability of data and knowledge networks for both long-term monitoring and evaluation of their policies, plans, and management and for adaptive decision making. The overall approach may enhance the scientific legitimacy of their decision making processes [26].

Academics and scientists may seek to increase the utility of their research and expertise. Students' education may be enhanced with experiences from local, relevant, real-life training. Researchers may be able to use monitoring and evaluation of policies, plans, and management to produce new scientific knowledge and develop new methods.

Strategic features are the third element of the framework. Strategic features in the framework are those elements of a platform that are designed and deployed to support multi-sectoral, interdisciplinary, and transdisciplinary collaborations. The key benefit to identifying strategic features is to understand how to build upon and create synergies from opportunistic activities to achieve the desired outcomes. The strategic features element is composed of participation and investments from multiple sectors—government, academic, non-profit, business, and community—and multiple disciplines to produce a community of social networks and teams, and boundary objects and boundary management (Figure 2).

A multi-sector and multi-discipline approach of social networks and teams can expand the resources, expertise,

Figure 2



Strategic features depend upon multiple sectors and disciplines to create communities of social networks, data, and knowledge systems.

and data that can be incorporated into solving transdisciplinary land system problems. It is important to note, however, that interdisciplinary and transdisciplinary approaches should not be accepted uncritically. On one hand, these types of approaches are time-intensive, require a willingness to work collaboratively and engage with and learn new concepts and terms, and test participants' abilities to both advance science and produce societal solutions [27]. On the other hand, these types of approaches represent opportunities to broaden interactions with diverse perspectives and solve complex problems that would otherwise be inscrutable from a disciplinary or sectoral perspective [28].

The use of boundary objects and participation of boundary organizations can be crucial for addressing some of the positive and negative issues associated with transdisciplinary approaches. The creation and use of boundary objects can be an essential process in developing cooperation and managing diversity across intersecting social worlds to address wicked, complex problems [29]. Boundary objects are intended to be useful in several ways. They "allow scientists to cooperate and work [collectively] 1) without having good models of each other's work; 2) while employing different units of analysis, methods of aggregating data, and different abstractions of data; and 3) having different goals, time horizons, and audiences to satisfy [30:46]." Boundary objects may be abstract or concrete. An important test of boundary objects is their ability to encompass, change, and adapt to multiple points of view while increasing communication across viewpoints [29]. This is essential for different actors to conceive of and negotiate transdisciplinary problems and to conceptualize how they fit in and identify appropriate roles for their participation [26,29].

There are at least four types of boundary objects: (1) repositories, (2) ideal types, (3) coincident boundaries, and (4) standardized forms and practices [29]. *Repositories* are ordered 'piles' of objects that are indexed in a standardized fashion. Data information systems are an example of a repository boundary object and can include a diversity of materials (piles) such as field data and field samples; interviews, and remote sensing and documentation with metadata. Data information management systems can span a broad range of disciplines and sectors. Often, information management systems may include multi-media such as publications, reports, presentations, briefing papers, photos, animations, and video. At the margin, arts and humanities can contribute substantially to transdisciplinary knowledge systems that support action.

Ideal types include diagrams and other forms of symbolic abstraction. They are not intended to accurately or precisely describe the details of a place or a thing. It is an abstraction from the relevant domains and may be fairly vague. "It serves as a means of communicating and cooperating symbolically—a 'good enough' road map for all parties" [29:410]. Ideal types or conceptual diagrams can include coupled [20] and co-produced system perspectives [31,32].

Coincident boundaries are often relatively familiar objects that have the same boundaries but may have different internal contents, depending upon the perspectives of various team members. These objects may be different types of nested geographies such as socio-political regions, municipalities, and neighborhoods, or climatic zones, geologic formations, or watersheds.

Standardized forms and practices are methods of common communication across dispersed work groups over space and time to facilitate cooperation and collaboration. For instance, projects may discuss plans and organize data collection teams so that physical, ecological and social data are co-located and synchronized. Strategies may be developed to link and integrate diverse data types such as field data, remotely sensed data, and administrative data with 'data hooks' that include latitude/longitude, address, time, and scale [33].

Boundary objects can exist independently or as a system. When they are used as a system, boundary objects can be used interactively. For instance, information management systems (repository) can be used to populate a conceptual diagram (ideal type) and applied to understand the social-ecological dynamics of a watershed (coincident boundaries). The use of boundary objects depends upon boundary organizations and boundary management [26]. Boundary management functions—communication, translation, and mediation—can be performed effectively through various organizational arrangements and procedures. These functions can be institutionalized in boundary organizations, organizations mandated to act as intermediaries between teams, disciplines, and sectors "As originally conceived, boundary organizations have at least three features: (i) they involve specialized roles within the organization for managing the boundary; (ii) they have clear lines of responsibility and accountability to distinct social arenas on opposite sides of the boundary; and (iii) they provide a forum in which information can be co-produced by actors from different sides of the boundary through the use of 'boundary objects'" [26:8089].

Teams versus teams of teams

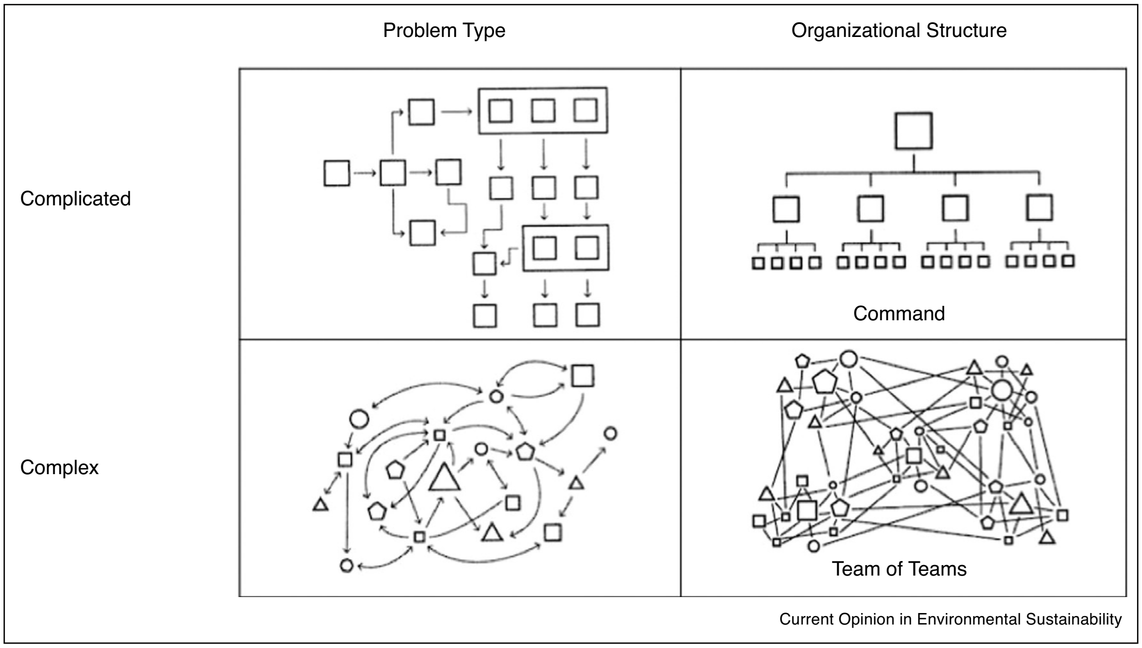
Just as boundary objects can be used to build cooperation to wicked, complex problems, McChrystal *et al.* [34] distinguish between the social organization and teamwork needed to solve complicated versus complex problems (Figure 3).

There are several critical features for teams, or teams of teams, to solve wicked, complex problems. These include a shift from emphasizing efficiency to adaptability as a core competency [34]. This requires changes to organizational structure, culture, and their interactions. McChrystal *et al.* [34] have found that what makes small teams adaptable are trust, common purpose, empowerment, and shared awareness.

Trust, common purpose, and empowerment are critical because they invigorate teams with an ability to solve problems that could never be foreseen by a single leader. Ideas and innovations often emerge from the bottom–up result of interactions, rather than from a top–down direction. Trust is crucial within a team and among teams. Strong lateral ties are critical for developing trust and the construction of shared awareness. However, every member of an entire project does not need to know everyone else on the project. Everyone on one team just needs to know at least one person on each of the other teams [34].

Attention to team building and nurturing is needed. Developing a culture, which includes standards, 'rules of the game,' and philosophy, is important [25,35,36]. There needs to be opportunities for social interactions to develop identity, trust, and bonding. Because participants enter with different experiences and expectations, formal and informal coaching and support for interdisciplinary, team, and applied science are vital functions. Finally, participation needs to address incentives and rewards for

Figure 3



The type of problem to be solved has important implications for the organizational structure adopted to solve the problem. This is true for both scientific and societal problems. Complicated problems can be broken down into its subcomponents without regard for interactions among subcomponents. In contrast, solutions to complex problems have to account for interactions among subcomponents.

each of the different sectors [28]. Enlightened self-interest, including benefits and values of participants, is crucial.

What are the differences between a transdisciplinary project and platform?

We propose that the contrast between short-term projects and long-term platforms falls along four dimensions: boundary objects; organizational structures; types and number of projects; and time. This list may not be exhaustive and the differences for each dimension are in degree and not categorical. Projects and platforms will both develop and use boundary objects and employ teams, or teams of teams, to tackle wicked, complex problems. However, the maintenance, reuse, and adaptation of boundary objects over time is an important feature for long-term platforms. Because of the longer-term nature of platforms, a team of teams approach has to consider how to recruit, acculturate, and retain new members and maintain boundary management. There are differences in the types of phenomenon most appropriate for projects and platforms. Projects may tend to focus on events occurring over months and years. They may also address extensive, pervasive, and subtle changes occurring over decades. This will be the case for platforms, too. However, the standing capacity and competencies of long-term platforms will predispose them to be more effective for providing real-time responses to unfolding crises and emergencies. Long-term platforms can also be a 'place' for the discovery, exploration, and prototyping of science and applications that are not pre-identified and are ill-defined. Finally, and perhaps the most obvious difference between projects and platforms is the dimension of time, where projects often last between two to five years, and platforms may persist for decades. This allows long-term platforms to adapt and evolve as a whole in contrast to engaging in a series of new projects.

Conclusion

Land system science can play a critical role in informing and negotiating shared sustainability pathways to more resilient socio-ecological systems. We argue that transdisciplinary science projects are not enough. We need durable platforms to solve wicked, complex land system problems from immediate crises and emergencies over days and weeks; to sudden events over months and years; to extensive, pervasive, and subtle changes occurring over decades.

It is important to recognize that the construction and maintenance of effective transdisciplinary platforms for land system science takes time and patience. Strategies and activities to promote such systems require a sufficiently long-term perspective in order to account for the slow impact of ideas on both science and practice, the need to learn from experience, and the time scales needed to develop the necessary human and institutional capital [26:8090]. Such a long-term perspective may span more than a decade, individual projects, and entire careers.

In this paper, we have provided a framework and described strategic features for transdisciplinary land system science platforms. These features can create synergistic results from opportunistic activities that are essential for both decision makers and scientists. The exact prescription for how to create these strategic features and the specific organizational arrangements depends upon local conditions. Ultimately, it is important to recognize that the purpose of such an endeavor is to enable and produce a collective capacity across sectors and disciplines to support more sustainable and resilient societies.

Conflict of interest statement

Nothing declared.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants # DEB-1637661, DBI-1052875, DBI-1639145, the USDA Forest Service, and the University of Maryland. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation, the USDA Forest Service, and the University of Maryland.

Drs. Margaret Palmer, Jonathan Kramer, and Cynthia Wei shared many insights into transdisciplinary research and team science while Grove was a visiting scholar at SESYNC. We also wish to thank the constructive suggestions of two anonymous reviewers and the guest editor for this manuscript.

References

1. Meyfroidt P, Chowdhury RR, de Bremond A, Ellis EC, Erb KH, Filatova T, Garrett RD, Grove JM, Heinimann A, Kuemmerle T, Kull CA: **Middle-range theories of land system change**. *Glob Environ Change* 2018, **53**:52-67.

2. Berkes F, Folke C, Colding J (Eds): *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge University Press; 1988.

3. Millennium Ecosystem Assessment (MA): *Ecosystems and Human Well-Being: A Framework for Assessment*. Washington, DC: Island Press; 2003.

4. Verburg PH, Crossman N, Ellis EC, Heinimann A, Hostert P, Mertz O, Nagendra H, Sikor T, Erb KH, Golubiewski N, Grau R: **Land system science and sustainable development of the earth system: a global land project perspective**. *Anthropocene* 2015, **12**:29-41.

5. Grove JM, Chowdhury R, Childers D: **Co-design, co-production, and dissemination of social-ecological knowledge to promote sustainability and resilience: urban experiences from the U.S. long term ecological research (LTER) network**. *Glob Land Proj News* 2015, **11**:6-11.

6. Grove JM, Childers DL, Galvin M, Hines S, Muñoz-Erickson T, Svendsen ES: **Linking science and decision making to promote an ecology for the city: practices and opportunities**. *Ecosyst Health Sustain* 2016, **2**:e01239.

7. Zscheischler J, Rogga S: **Transdisciplinarity in land use science–a review of concepts, empirical findings and current practices**. *Futures* 2015, **65**:28-44.

8. Börner K, Contractor N, Falk-Krzesinski HJ, Fiore SM, Hall KL, Keyton J, Spring B, Stokols D, Trochim W, Uzzi B: **A multi-level systems perspective for the science of team science**. *Sci Transl Med* 2010, **2** 49cm24-49cm24.

9. Angelstam P, Andersson K, Annerstedt M, Axelsson R, Elbakidze M, Garrido P, Grahn P, Jönsson KI, Pedersen S, Schlyter P, Skärbäck E: **Solving problems in social–ecological systems: definition, practice and barriers of transdisciplinary research**. *Ambio* 2013, **42**:254-265.

10. Buizer M, Ruthrof K, Moore SA, Veneklaas EJ, Hardy G, Baudains C: **A critical evaluation of interventions to progress transdisciplinary research**. *Soc Nat Resour* 2015, **28**:670-681.

11. Childers DL, Cadenasso ML, Grove JM, Marshall V, McGrath B, Pickett ST: **An ecology for cities: a transformational nexus of design and ecology to advance climate change resilience and urban sustainability**. *Sustainability* 2015, **7**:3774-3791.

12. Pearce B, Adler C, Senn L, Krütli P, Stauffacher M, Pohl C: **Making the link between transdisciplinary learning and research**. *Transdisciplinary Theory, Practice and Education*. Cham: Springer; 2018, 167-183.

13. SEYSNC: *Social-Environmental Immersion Program for Post-Graduate Fellows*. https://www.sesync.org/for-you/educator/programs/immersion. [Accessed 2 January 2019].

14. National Science Foundation: *Dear Colleague Letter: Growing Convergence Research*. https://www.nsf.gov/pubs/2018/nsf18058/nsf18058.jsp. [Accessed 4 January 2019].

15. Belmont Forum. *Transdisciplinary Science Funding Opportunities*. http://www.belmontforum.org/opportunities/. [Accessed 4 January 2019].

16. Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George P: **The causes of land-use and land-cover change: moving beyond the myths**. *Glob Environ Change* 2001, **11**:261-269.

17. Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Ostrom E: **Complexity of coupled human and natural systems**. *Science* 2007, **317**:1513-1516.

18. Simon D, Schiemer F: **Crossing boundaries: complex systems, transdisciplinarity and applied impact agendas**. *Curr Opin Environ Sustain* 2015, **12**:6-11.

19. Duckett D, Feliciano D, Martin-Ortega J, Munoz-Rojas J: **Tackling wicked environmental problems: the discourse and its influence on praxis in Scotland**. *Landsc Urban Plann* 2016, **154**:44-56.

20. Collins SL, Carpenter SR, Swinton SM, Orenstein DE, Childers DL, Gragson TL, Grimm NB, Grove JM, Harlan SL, Kaye JP *et al.*: **An integrated conceptual framework for social-ecological research**. *Front Ecol Environ* 2011, **9**:351-357.

21. Machlis GE, McNutt MK: **Scenario-building for the deepwater horizon oil spill**. *Science* 2010, **329**:1018-1019.

22. Grove JM, Pickett STA, Whitmer A, Cadenasso ML: **Building and urban LTSER: the case of the Baltimore ecosystem study and the D.C./B.C., ULTRA-Ex project**. In *Long Term Socio-Ecological Research Studies in Society Nature Interactions Across Temporal and Spatial Scales.* Edited by Singh JS, Haberl H, Schmid M, Mirtl M, Chertow M. Dordrecht: Springer; 2013:369-408.

23. Mirtl M, Orenstein DE, Wildenberg M, Peterseil J, Frenzel M: **Development of LTSER platforms in LTER-Europe: challenges and experiences in implementing place-based long-term socio-ecological research in selected regions**. *Long Term Socio-Ecological Research*. Netherlands: Springer; 2013, 409-442.

24. Angelstam P, Manton M, Elbakidze M, Sijtsma F, Adamescu MC, Avni N, Beja P, Bezak P, Zyablikova I, Cruz F, Bretagnolle V: **LTSER platforms as a place-based transdisciplinary research infrastructure: learning landscape approach through evaluation**. *Landsc Ecol* 2018:1-24.

25. Holzer JM, Adamescu MC, Díaz-Delgado R, Dick J, Grove JM, Rozzi R, Orenstein DE: **Negotiating local vs. global needs in the**

International Long Term Ecological Research (ILTER) Network's socio-ecological research agenda. *Environ Res Lett* 2018, **13**:105003.

26. Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jäger J, Mitchell RB: **Knowledge systems for sustainable development**. *Proc Natl Acad Sci U S A* 2003, **100**:8086-8091.

27. Barry A, Born G, Weszkalnys G: **Logics of interdisciplinarity**. *Econ Soc* 2008, **37**:20-49.

28. Pickett STA, Grove JM, LaDeau SL, Rosi EJ: **Urban ecology as an integrative science and practice**. In *Urban Ecology—It's Nature and Challenges.* Edited by Barbosa do. Wallingford, UK (Boston, MA, USA): The Center for Agriculture and Bioscience International; 2019.

29. Star SL, Griesemer JR: **Institutional ecology, translations, and boundary objects: amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39**. *Soc Stud Sci* 1989, **19**:387-420.

30. Star SL: **The structure of ill-structured solutions: boundary objects and heterogeneous distributed problem solving**. *Distributed Artificial Intelligence*. Morgan Kaufmann; 1989:37-54.

31. Redman CL, Grove JM, Kuby LH: **Integrating social science into the long-term ecological research (LTER) network: social dimensions of ecological change and ecological dimensions of social change**. *Ecosystems* 2004, **7**:161-171.

32. Rademacher A, Cadenasso ML, Pickett ST: **From feedbacks to coproduction: toward an integrated conceptual framework for urban ecosystems**. *Urban Ecosyst* 2018:1-12.

33. Grove JM, Cadenasso ML, Pickett ST, Machlis GE, Burch WR: *The Baltimore School of Urban Ecology: Space, Scale, and Time for the Study of Cities*. Yale University Press; 2015.

34. McChrystal GS, Collins T, Silverman D, Fussell C: *Team of Teams: New Rules of Engagement for a Complex World*. Penguin; 2015.

35. Pickett STA: **The culture of synthesis: habits of mind in novel ecological integration**. *Oikos* 1999, **87**:479-487.

36. Pickett STA, Burch WR, Grove JM: **Interdisciplinary research: maintaining the constructive impulse in a culture of criticism**. *Ecosystems* 1999, **2**:302-307.