Chapter 7

Sustainability science as a management science

Beyond the natural–social divide

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Introduction: sustainability science as a management science

Sustainability science is an interdisciplinary enterprise devoted to exploring, understanding, and ultimately actively contributing to transformations towards more sustainable configuration of social systems (Kates et al. 2001; Jerneck et al. 2011; Komiyama and Takeuchi 2006). The field emerged out of discussions, especially in the 1980s, around sustainability and sustainable development and has in recent years developed into a full-fledged and very active inter-discipline. Interdisciplinarity remains a central methodological challenge, a core value, and is ultimately an essential feature of how the field understands itself (Jerneck et al. 2011; Persson et al. 2018; Thorén et al. forthcoming).

In the discussions of interdisciplinarity in sustainability science, the main emphasis has almost always been on how to bridge the natural and the social sciences (Kates et al. 2001; Jerneck and Olsson 2020; Persson et al. 2018). Seeing the divide between natural and social sciences as the main obstacle for interdisciplinarity in sustainability science, however, is of limited heuristic use and can even be misleading. First of all, sustainability science explicitly models the complex couplings of natural and social systems, at bigger or smaller scales, which means that their target domain is both natural and social. Therefore, at the ontological level the natural–social divide cannot be the dividing line, because modeling has to deal with both (DesRoches et al., 2019).

Second, on the epistemic or methodological level, the often-emphasized divide between quantitative or formal approaches of natural science and the qualitative or informal approaches of social science is a false dichotomy because these differences do not map onto the natural–social divide at all. Economists and sociologists use mathematical and statistical modeling approaches as much as chemists and biologists; evolutionary theory was initially formulated in a verbal, non-formal way. As we will show below, coupled management models have both natural and social components.

Finally, on the practical level, sustainability science has explicit orientations toward certain sustainability goals and societal transitions, which do not fit it into either the natural or the social science camps. The received view in the philosophy of science is that *science*—natural or social—is a value-neutral, primarily epistemic enterprise, at least as an ideal. The explicit commitments to sustainability goals of sustainability science are unique in this respect, and rather comparable to systems engineering or operations research (OR), which applies "scientific methods, techniques and tools to problems involving the operations of a system so as to provide those in control of the system with the optimum solution to the problem" (Churchman, Ackoff, and Arnoff, 1957, quoted in Strijbos, 2017, 295). Gass and Assad (2005, ix) note that

> OR is not a natural science. OR is not a social science. OR's distinguishing characteristic is that OR applies its scientific and technological base to resolving problems in which the human element is an active participant. As such, OR is the science of decision making, the science of choice.

The operational scales and scientific bases of sustainability science can be different from those of OR, but it is similarly committed to "resolving problems in which the human element is an active participant." The connection between sustainability science and operations research is more direct in the fields that deal with resource management such as fisheries management (Lane 1989; Lane and Stephenson 1995). In what follows we call a science that concerns decision-making in pursuit of certain goals a *management* science, following Herbert Simon (1960). Sustainability science is a management science aiming at sustainability goals.

Thus characterized, the next question is where the sustainability goals of decision-making come from. Here the contrast between natural and social science surfaces again as a *conflict of value-orientations*. For example, in fisheries management there are two conflicting goals, namely resource allocation and conservation, studied by economics and biology, respectively. In ecological economics there has been a long debate over the extent to which natural capital is substitutable with other kinds of capital, where economists tend to defend substitutability while ecologists defend non-substitutability. Because of this association, one might think that each science has conflicting values: social science for achieving human-centered values; biology and ecology for the conservation of non-human species and environments. This association, however, is weak because if one sufficiently values long-term intergenerational human welfare, then anthropocentric utilitarianism is often compatible with conservation. The question ultimately becomes what the appropriate discounting rate for the welfare of future generations should be, which is a political and ethical question of intergenerational justice that does not divide natural and social scientists.[1]

Whether there exist values independent of humans as valuers (current or future) is a meta-ethical question that, again, is not necessarily tied to the natural–social divide. Moreover, valuing nature for its own sake, independently of human existence, is operationally equivalent to the current generation subjectively valuing non-use of nature, independently from its instrumental benefit to the present or future generations. Also, seeing natural science as value-free and social science as value-laden and more like ethics is also unhelpful, as we will argue later in this chapter.

An orthogonal contrast is that between social science as a critical reflection on certain prevalent social values (such as sustainability) versus natural science, which naively presupposes those values to be quantified and controlled (see, e.g., Mingers 1992, for a critique of traditional management science from a perspective of critical theory). The distinction between problem-solving science that takes various social values as it finds them and develops solutions in accordance with those values, and critical science that targets and questions those very values (see, e.g., Mahmoud et al. 2018), which has sometimes been emphasized in sustainability science, comes to mind. Note, however, that reflexivity or critical awareness as such does not make a study value-neutral or value-superior relative to more naïve scientific and management practices. Thus, we consider it to be more fruitful to incorporate social scientific reflexivity as a useful resource for better sustainability science, rather than seeing it as a methodological obstacle that deeply divides natural and social scientists in the field.

In sum, if we understand sustainability science as a kind of management science that draws on various scientific bases, then there is no stable or deep line that divides natural and social scientific elements in it, either at the ontological, methodological, or ethical levels. Our point is not that there are no such correlations to be identified, but rather that this line is not the most challenging obstacle in addressing interdisciplinary challenges to advance sustainability science. In the next section, we argue that an alternative, more interesting divide may be found between the so-called *soft* and *hard* systems thinking.

Systems thinking, soft and hard

Systems thinking is a family of approaches that has motivated a variety of inter- and transdisciplinary movements in science and technology in the second half of the 20th century (Strijbos 2017). It was originally conceived as a *general systems theory* that can unify the sciences by modeling any given target of inquiry as a functional "system" operating and situated in a given environment, rather than a machine with parts to be studied separately by different disciplines. Prominent proponents of systems theory include the biologist Ludwig von Bertalanffy (1901–1972) and the economist Kenneth E. Boulding (1910–1995). Such a theoretical unification, however, has not taken place within natural sciences, within social sciences, or between them. Instead we have seen proliferation of subfields and interfields in science, somewhat contrary to the ideal of the unification of the sciences.

Perhaps the influence of systems thinking is more prominent in engineering and management than in scientific theorizing.[2] In these domains, systems thinking took root during World War II, giving rise to the post-war OR and to management science. Systems thinking shifted the target of engineering from technical artifacts to larger systems comprising human-artifact complexes, whose functions should be tweaked to achieve a desired goal identified by the analysis. Strijbos (2017, 296, quoting Checkland 1978, 107) characterizes the essence of systems engineering as follows: "There is a desired state, S(1), and a present state S(0), and alternative ways of getting from S(0) to S(1)." Problem solving, according to this view, consists of "defining S(1) and S(0) and selecting the best means of reducing the difference between them." According to this characterization, "hard" systems thinking is nothing other than what philosophers call *instrumental rationality*. As such, it is nothing new and it is difficult to refute its centrality in any goal-directed enterprises. What was new in the postwar period, however, were the developments in decision theory and game theory that provided axiomatic foundations for instrumental rationality, opening a path toward rigorously operationalizing the means and ends in applied contexts. In particular, Expected Utility Theory (von Neumann and Morgenstern 1944; Savage 1954) gave a clear operational meaning to subjective beliefs and expected utilities, as well as their interactions, and game theory (von Neumann and Morgenstern 1944; Nash 1951) provided powerful tools to analyze the aggregate-level behavior of a system consisting of agents whose interests converge and diverge to a varying degree.

Motivated by the perceived failure of these formal approaches to provide satisfactory results in many real-world management situations, Peter Checkland (1930–) proposed what is now called *soft systems methodology* (SSM), or soft systems thinking. SSM was developed to resolve unstructured management, planning, and public policy situations involving multiple objectives that are often unclear or contradictory (Gass and Assad 2005, 160). Such problems were characterized as "wicked problems" around the same time (in 1967) by the planning theorist Horst Rittel (Skaburskis 2008). While "tame" or technical problems can be solved by directly applying the "hard" systems approaches such as mathematical and statistical modeling, mathematical programming, computer simulation and decision and game theory, wicked problems are not well-formulated, and as such resist straightforward applications of instrumental rationality, instead requiring a sort of perspectival shift. Similar calls for a shift in OR thinking were also made by Russell Ackoff (1919–2009) and West Churchman (1913–2004) in the USA. The contrast emphasized by Checkland (2000) is represented in Figure 7.1.

Hard systems thinkers take a system modeled as if existing in the world, which can be engineered from "outside"; soft systems thinkers take a model

Figure 7.1 The contrast between hard and soft systems stances.

Inter- and Transdisciplinarity in Bioeconomy – Scientific Figure on ResearchGate. www.researchgate.net/figure/Systems-practice-in-interdisciplinary-research-Ison-2010-Fig-434-adapted-from_fig5_321777799 [accessed Jan. 2021]

as a learning tool to organize the process of inquiry. This is a meta-methodological difference in stance toward the system: the hard stance sees it as a model of reality, while the soft stance sees it as a model of the inquirer's own thinking about the world. A similar contrast figures in the metaphysical debates between scientific realism and instrumentalism in the philosophy of science, but note that the hard–soft distinction is not a metaphysical but meta-methodological one that highlights two complementary outlooks. In management science, many models are directly or indirectly connected to the problem situation to be resolved in a practical sense. For example, mathematical programming in a resource management context gives a model of the problem-solution set: an objective function defines the problem as a mathematical one of finding the optimal management strategy given the constraints coming from the behavior of the system components, such as fish stock or tree growth. In this context, no one would debate over whether such a model as a whole (in contrast to its components models) represents the reality that exists independently from the modeler as a problem solver (it clearly doesn't). Rather, what is highlighted by the soft systems stance is the fact that such a way of representing the problem situation is *one of many ways* the problem situation at hand can be formulated, which is not necessarily shared with other modelers or the agents modeled (who are often called stakeholders).

Why is the soft–hard stance a relevant distinction for sustainability science and the challenges of achieving inter- and transdisciplinarity? First, if we understand sustainability science as a kind of management science with specific goals, as we proposed in the last section, then the choice of particular modeling approaches must have justifications—implicit or explicit—for its problem-formulation, distinct from the usual epistemic ones, such as empirical accuracy and explanatory power. The enduring disagreements across scientific disciplines concerning sustainability—such as between ecologists and economists—can be partly explained if we assume that those from different disciplinary backgrounds tend to take a hard stance toward their own well-developed, so-called legacy models. We can better understand self-identified sustainability scientists (unlike, say, biologists or economists who study sustainability issues) who lament this state of interdisciplinary disagreements and call for more genuine inter- and transdisciplinary sustainability science (e.g., Dorninger et al., 2020) if we interpret them as promoting soft systems thinking. These scholars have no presumption that sustainability science will eventually lead to a unified theory dreamed by general systems theorists. Instead, they reiterate the plurality and relativity of perspectives and highlight the importance of developing methods to arrive at a shared framing of the problem situation among the modelers and between the modelers and the modeled agents.

In OR, soft systems thinking is operationalized as a family of methods called *problem structuring methods* (PSMs) (Smith and Shaw 2019). Among others, these methods share two important characteristics. The first one is that PSMs model subjective interpretations of the problem situation. This is exactly the main point of soft OR discussed above. It is naturally followed by the second characteristic, which is that PSMs actively involve stakeholders, namely those agents who have to make management decisions (e.g., authorities) and those agents who are modeled in the management model (e.g., fishermen). The second follows from the first because once the model is seen as a subjective construal of the problem situation, some validation mechanism is needed to ensure that the problem situation is intersubjectively shared. Such validation processes are expected to bring various benefits, including the enhancement of participants' learning about the situation, development of buy-in to politically feasible outcomes, and legitimization of the decisions through procedural rationality. In the literature on interdisciplinarity, transdisciplinarity is characterized either as an advanced form of interdisciplinary integration of theories, models and concepts (e.g., in systems dynamics models), or as co-production of knowledge and solutions through the involvement of extra-scientific participants (Bernstein 2015). Sustainability scientists tend to adopt the latter, operational definition of transdisciplinarity as stakeholder engagement, which suggests that they subscribe to soft OR. Those who are skeptical about the merits of co-production, in contrast, are implicitly adopting a hard stance and *ipso facto* assuming that the experts' problem-framing is the correct one.

Now that we have introduced what we think is a relevant distinction, soft and hard systems thinking in sustainability science, we will look at two cases of model-based sustainability science. We show that, despite the divide, it is possible to make use of both perspectives in a productive way.

How to use the soft and hard distinction: two illustrative cases

In the last two sections, we argued that the soft–hard distinction is more fundamental than the natural–social divide in sustainability science. What we mean by "fundamental" is not that the divide is impossible to bridge, but rather that it is a useful explanatory hypothesis to understand the unique interdisciplinary landscape in sustainability science. In this section, we will argue that noticing the soft–hard distinction is also useful for advancing sustainability science methodologically. The key idea is that, since soft systems thinking involves a shift in perspective or stance, you can improve existing "hard" looking management models in a "soft" direction, without abandoning these models or coming up with entirely new models.

Game theory in natural resource management

Game theory, which is mentioned in the last section, is a poster child of postwar social science. It is a versatile theory of interactive decision-making that can model interactions of any $n \geq 2$ agents—human or non-human agents such as states, groups, ants, and behavioral phenotypes. It can model non-cooperative as well as cooperative interactions. It has stimulated the explosion of experimental studies of human and system behavior in economics, political science, psychology, sociology, and anthropology, and its use goes beyond social science and into evolutionary biology. When seen as a tool in OR, game theory provides a typical "hard" systems analysis. It models a problem situation as consisting of a set of *players*, who have a set of *actions*, which defines *outcomes* as the combination of the actions; each player has a preference ordering over these outcomes, and acts so as to satisfy her preference ordering, given that the other players are doing the same. *Solution concepts*, most importantly the Nash equilibrium, define how such games are "solved" at a steady state in which no player can do better by unilaterally changing her course of action.

The use of game theory is traditionally categorized into *descriptive* and *prescriptive* uses. In the descriptive use, the game theorist-qua-observer uses the model as a scientific representation of a given strategic situation to be studied, in order to understand, explain, predict, and intervene in the behavior of the system. The descriptive use corresponds to hard systems thinking, in that the modeler assumes that the modeled situation exists "outside" the observer. For example, think about any social dilemma situation such as common resource management. The present state S(0) (e.g. overfishing) can be identified as a socially sub-optimal Nash equilibrium, and the desired state S(1) is identified as an alternative outcome that is beneficial to all players involved (which may or may not be Nash). Finally, several options to change S(0) to S(1) are considered, such as changing incentives, beliefs, or some other aspects of the game through regulations. Many of the current uses of game theory for policy purposes are based on this descriptive hard stance.

In the prescriptive (or normative) use, in contrast, the game theorist-qua-consultant provides a player (the client) with recommendations as to what he should do in order to satisfy his preferences. A good example of this is the involvement of the game theorist Thomas Schelling in strategic planning during the Vietnam War. The validity of such recommendations is based on the descriptive accuracy of the model (who the players are, what options they have, what they prefer, whether they are "rational," etc.), which in turn depends partly on the recommendations themselves because the client and his understanding of the situation are also part of the game.[3] In this sense, the prescriptive use calls for a soft stance, because the specification of the problem situation is inescapably subjective, and therefore inter-subjective validation of the model is essential for the success of the recommendations, such as that "threats must be credible." Did North Vietnam see the situation the same way as the Pentagon? Were they playing the same game to begin with? Of course, in conflict situations the challenge is that the stakeholders may have incentives *not to share* their perspectives or available options, but regardless of these strategic subtleties, our point should be clear. There is nothing essentially "hard" in game theory, despite its strong axiomatic foundations and mathematical formalism. Game theory in itself is neither hard nor soft, but its use can be.

The explicit soft use of game theory is apparent in what Redpath et al. (2018, 418) call a *constructivist* approach to the management of conservation conflicts, according to which "games are designed and used in iterative processes to understand conflict situations and help stakeholders to come up with solutions." In particular, unlike the standard use of experimental games in economics, which, based on the hard stance, adheres to a set of strict methodological precepts, such as the use of real incentives and subject anonymity to guarantee experimental control for valid causal inferences, the constructive approach gives players "freedom to explore a range of possible outcomes in strategic situations such that they can reframe the problem and the game, and create new options not initially contemplated by the research team" (Redpath et al. 2018, 418). For example, Worrapimphong et al. (2010), in looking for sustainable fishing practices for the razor clams in a coastal wetland in the Gulf of Thailand, combined role-playing games, computer simulation of agent-based models, and co-exploration of the situation with stakeholders (local government officials and fishermen and women). The researchers used game theory as a problem-structuring template, and constructed the problem and solutions together with those who are modeled, instead of studying the problem situation as external to them and devising intervention strategies from "outside." Behavioral and perspective changes of the involved parties are expected outcomes of the constructivist approach, not something to be suppressed and controlled. (See Redpath et al., 2018, 419, for another example of the use of the constructivist approach to the agro-forestry system in India.) The constructivist approach is under-explored in natural and social sciences, but as this example illustrates, the theoretical, experimental, and computational resources of game theory can be readily exploited by sustainability scientists as soft systems thinkers.

Expected Utility Theory in the Integrated Assessment Model for climate action

Expected Utility Theory (EUT) has a similar wartime history as game theory. In fact, its first axiomatization was made by von Neumann and Morgenstern in the process of developing game theory (published in the 1947 second edition of von Neumann & Morgenstern 1944). EUT is still the standard model of individual decision-making under uncertainty, according to which the optimal action can be identified, given the probabilities of different outcomes, and the decision-maker's attitude toward risk in terms of risk preferences. The latter can be quantitatively measured as expected utilities that are unique up to positive affine transformation, but more intuitively categorized qualitatively into risk averse, risk neutral, or risk seeking. When the probabilities are interpreted as subjective degrees of beliefs of the decision-maker that follow certain rules of probability calculus as in Savage (1954), then the theory is sometimes called Subjective EUT. Just like game theory, EUT has two interpretations, descriptive and prescriptive (or more commonly called normative). Descriptively EUT is seen as a predictive or explanatory model of how the agent (typically a human) makes decisions, while prescriptively it is seen as a model that tells the decision-maker what the rational course of action to follow is, given her beliefs and preferences. Again, the descriptive–prescriptive distinction roughly corresponds to the hard–soft systems thinking in OR. While behavioral economists and psychologists took a hard stance and produced a lot of alternative descriptive models of choice under uncertainty, EUT still remains as the most widely accepted normative model. In other words, EUT is the dominant problem-structuring framework for situations involving uncertainty.

In sustainability contexts too, EUT is featured as a normative model to identify ideal climate mitigation strategies that maximize intergenerational expected utility, where "the decision-maker" is the whole of humanity (including both present and future generations), and the utility is operationalized as the net present value of the aggregate Gross Domestic Products (GDPs). To do this, an inter-temporal decision model complements

EUT by specifying time-preferences (in terms of the discounting rate for the future utilities) in addition to risk preferences. A so-called Integrated Assessment Model (IAM) couples this decision-theoretic framework with some model of the macroeconomy and equations that relate atmospheric concentration of GHGs to economic growth by way of surface temperature changes (which is called a *damage function*).[4] These damage functions are central to the outcome of the model but are typically very simplistic constructs. In one of the most influential IAMs in current use, William Nordhaus's Dynamic Integrated Climate-Economy model (DICE), the damage function is a quadratic function (Nordhaus 2017) and although they are rarely significantly more sophisticated (Pindyck 2013; 2017) standardly there is some observational basis (See Nordhaus 2017).[5]

Since this normative use of EUT in IAMs is in principle soft, according to our distinction, one can question whether it is a good way to frame the problem-situation humanity is facing, independently from questioning whether its components, such as the damage function, are accurate enough. Consider for example Winsberg's (2018, 123, 125) following comments on the use of IAMs: there are "voices coming particularly from the world of economics, who believe that how we should act in response to the threat of climate change is a scientifically discoverable fact," but "there is no scientific, as opposed to ethical, argument that one can make for" the claim that a certain discounting rate is justified; the IPCC's adoption of classical decision theory "is not a scientifically warranted conclusion" (Winsberg 2018, 126). "While it may very well be true that, in policy making, we have to make [value trade-offs], it doesn't follow that any particular choice of how to do this is scientific" (p. 127); IAMs "cannot be presented as more scientific alternatives to politically deliberated goals like the Paris goals" (p. 128).

In these quotes, Winsberg (2018) criticizes economists for pretending to do *science* (modeling reality) when in fact they are doing *ethics* (making value-laden decisions). However, we find the science–ethics dichotomy is ultimately unhelpful for advancing climate science. This is because the dichotomy cannot explicitly separate two distinct questions. One is the question of the frame-choice—is EUT a good problem-framing? The other is the question of the value choice in a given frame—should the discounting rate be 3% or less? Regarding the first question, Winsberg does not offer any alternative to EUT as a problem-framing template, insisting that it is not a scientific but an ethical or a political question. But in answering the second question in passing with his favorite discounting rate (Winsberg 2018, 125 n. 7), Winsberg in fact implicitly adopts the EUT framework (as otherwise, he cannot start arguing for any value of the discounting rate). Also, his claim that stakeholders should be consulted to determine their true risk preferences (rather than using the default assumption of risk neutrality) suggests that he accepts the EUT framework as the ring on which to play sumo with economists, as it were.

The soft–hard distinction in systems thinking can help us avoid this type of conflation, by pointing out that the prescriptive use of decision theory such as EUT is essentially soft. Winsberg is frustrated with economists because they seem to take a hard stance toward EUT, but his criticisms, on close inspection, reveal that he accepts the usefulness of the problem-framing to operationalize intergenerational ethical decisions and to involve stakeholders. EUT however is one of many frameworks for modeling the problem-situations involving uncertainties. In fisheries management science, for example, practitioners from different disciplinary backgrounds actively discuss the pros and cons of a range of alternatives, such as Multi Criteria Decision Analysis, Bayesian Belief Network analysis with the use of Influence Diagrams, etc. (see Benson and Stephenson, 2018). For philosophers to understand and contribute to these methodological discussions, it is crucial to notice the soft–hard distinction in systems thinking, and in particular the soft realization that sustainability scientists as modelers are part of the sustainability problems they try to understand and solve.

Conclusion

In this chapter, we have argued that, in order to understand the interdisciplinary and transdisciplinary dialectics in sustainability science, it is useful to see sustainability science as a kind of management science, and then highlight the hard–soft distinction in systems thinking for OR. In the first section we argued that the natural–social science dichotomy is relatively unimportant and unhelpful. In the second section, we outlined the differences between soft and hard systems thinking as a more relevant and helpful distinction, mainly as a difference between perspectives toward systemic modeling. Then we argued that the distinction is methodologically useful in advancing sustainability science, either to open up a possibility of using existing theoretical, experimental, and computational resources of the sciences in a soft way (the case of game theory), or to make explicit what exactly is at stake when particular disciplines (such as economics) are criticized (the case of EUT/IAMs).

Notes

1 A salient example is Tyler Cohen, a prominent liberal economist who argues that there should be no discounting at all across generations. Although he is in the minority, this suggests that the rate of discounting is a philosophical question that does not map onto the natural–social science divide.

2 Although we follow Strijbos (2017) in separating science and engineering as two domains in which systems thinking was applied, the reality is more complicated. In particular, systems thinking itself blurs the distinction between pure theory and applied domains. See also Mirowski (2002).

3 Philosophers and sociologists of science characterize this way in which theory and reality are entangled as the *performativity* of scientific theories.

4 Although this type of IAMs is most frequently discussed, there are many different kinds of IAMs and not all of them are aggregated in this way, or even contain damage functions. See, e.g., Beck and Krueger (2016) for a helpful overview.

5 Interestingly with respect to both damage function and time-preference a debate has been raging among climate economists since Nicholas Stern's famous report was published (Stern 2007) about how to view these crucial parameters. Stern favored a "normative" approach, thinking of especially time-preference as an ethical or policy issue, whereas, e.g., Nordhaus favored a "descriptive" stance taking these parameters to be quantities to be measured or estimated with uncertainties. See also Beck and Krueger (2016).

References

Beck, M. & Krueger, T. (2016). The Epistemic, Ethical, and Political Dimensions of Uncertainty in Integrated Assessment Modeling. *Wiley Interdisciplinary Reviews: Climate Change* 7 (5), 627–645.

Benson, A. & Stephenson, R. L. (2018). Options for Integrating Ecological, Economic, and Social Objectives in Evaluation and Management of Fisheries. *Fish and Fisheries* 19 (1), 40–56.

Bernstein, J. H. (2015). Transdisciplinarity: A Review of its Origins, Development, and Current Issues. *Journal of Research Practice* 11 (1), 1–20.

Checkland, P. (2000) Soft Systems Methodology: A Thirty Year Retrospective. *Systems Research and Behavioral Science* 17, S11–58.

DesRoches, C. T., Inkpen, S. A. & Green, T. L. (2019) The Eroding Artificial-Natural Distinction? Some Consequences for Ecology and Economic. In Nagatsu, M. & Ruzzene, A., eds. *Contemporary Philosophy and Social Science: An Interdisciplinary Dialogue*. Bloomsbury Publishing, 39–57.

Dorninger, C., Abson, D. J., Apetrei, C. I., Derwort, P., Ives, C. D., Klaniecki, K., … & von Wehrden, H. (2020). Leverage Points for Sustainability Transformation: A Review on Interventions in Food and Energy Systems. *Ecological Economics* 171, 106570.

Gass, S. I. & Assad, A. A. (2005). *An Annotated Timeline of Operations Research: An Informal History*. Kluwer Academic Publishers.

Jerneck, A. & Olsson, L. (2020) Theoretical and Methodological Pluralism in Sustainability Science. In Mino, T. & Kudo, S., eds. *Framing in Sustainability Science.* Science for Sustainable Societies. Springer, 17–33.

Jerneck, A., Olsson, L., Ness, B., Anderberg, S., Baier, M., Clark, E., … & Persson, J. (2011). Structuring Sustainability Science. *Sustainability Science* 6 (1), 69–82.

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., … & Faucheux, S. (2001). Sustainability Science. *Science* 292 (5517), 641–642.

Knierim, A., Laschewski, L. & Boyarintseva, O. (2018). Inter- and Transdisciplinarity in Bioeconomy. In I. Lewandowski, ed., *Bioeconomy*. Springer, 39–72.

Komiyama, H. & Takeuchi, K. (2006). Sustainability Science: Building a New Discipline. *Sustainability Science* 1 (1), 1–6.

Lane, D. (1989). Operational Research and Fisheries Management. *European Journal of Operational Research* 42, 229–242.

Lane, D. and Stephenson, R. L. (1995). Fisheries Management Science: The Framework to Link Biological, Economic, and Social Objectives in Fisheries Management. *Aquatic Living Resources* 8, 215–221.

Mahmoud, Y., Jerneck, A., Kronsell, A. & Steen, K. (2018). At the Nexus of Problem-Solving and Critical Research. *Ecology and Society* 23 (4), 40–55.

Mingers, J. (1992). Recent Developments in Critical Management Science. *Journal of the Operational Research Society* 43, 1–10.

Mirowski, P. (2002). *Machine Dreams: Economics Becomes a Cyborg Science*. Cambridge University Press.

Morgenstern, O. & von Neumann, J. (1953). *Theory of Games and Economic Behavior.* Princeton University Press.

Nash, J. (1951). Non-Cooperative Games. *Annals of Mathematics* 286–295.

Nordhaus, W. D. (2017). Revisiting the Social Cost of Carbon. *Proceedings of the National Academy of Sciences of the United States of America* 114 (7), 1518–1523. https://doi.org/10.1073/pnas.1609244114.

Norton, B. G. (2015). *Sustainable Values, Sustainable Change: A Guide to Environmental Decision Making*. Chicago University Press.

Persson, J., Hornborg, A., Olsson, L. & Thorén, H. (2018). Toward an Alternative Dialogue between the Social and Natural Sciences. *Ecology and Society* 23 (4), 14–55.

Pindyck, R. S. (2013). The Climate Policy Dilemma. *Review of Environmental Economics and Policy* 7 (2), 219–237.

Pindyck, R. S. (2017). The Use and Misuse of Models for Climate Policy. *Review of Environmental Economics and Policy* 11 (1), 100–114.

Redpath, S. M., Keane, A., Andrén, H., Baynham-Herd, Z., Bunnefeld, N., Duthie, A. B. … & Pollard, C. R. (2018). Games as Tools to Address Conservation Conflicts. *Trends in Ecology and Evolution* 33 (6), 415–426.

Savage, L. J. (1954). *The Foundations of Statistics*. John Wiley.

Simon, H. A. (1977/1960). *The New Science of Management Decision*. Revised ed., Prentice-Hall.

Skaburskis, A. (2008). The Origin of "Wicked Problems". *Planning Theory and Practice* 9 (2), 277–280.

Smith, C. M. & Shaw, D. (2019). The Characteristics of Problem Structuring Methods: A Literature Review. *European Journal of Operational Research* 274 (2), 403–416.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press.

Strijbos, S. (2017). Systems Thinking. In Frodeman, R., Klein, J. T., & Pacheco, R. C. S., eds. *The Oxford Handbook of Interdisciplinarity*. Oxford University Press, 291–302.

Thorén, H., Nagatsu, M. & Schönach P. (forthcoming) An Interdisciplinary Sustainability Science? In Krieg, P. & Toivonen, R., eds. *Situating Sustainability: A Handbook of Contexts and Concepts*. Helsinki University Press.

von Neumann, J. & Morgenstern, O. (1944). *Theory of Games and Economic Behavior*. Princeton University Press.

Winsberg, E. (2018). *Philosophy and Climate Science*. Cambridge University Press.

Worrapimphong, K., Gajaseni, N., Le Page, C. & Bousquet, F. (2010). A Companion Modeling Approach Applied to Fishery Management. *Environmental Modelling and Software* 25 (11), 1334–1344.