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Structured output methods and environmental issues: perspectives on co-created bottom-up and 'sideways' science

Richard Taylor [1✉], John Forrester [1], Lydia Pedoth [2] & David Zeitlyn [3]

Participatory methods for researching human–environmental interactions seek detailed inputs on all manner of issues, but the outputs are often only understandable to the technically literate. On the other hand, participatory methods that involve the co-design of structured outputs (maps, models, games, stories, etc.) can be used to represent and integrate the knowledge and views of participants authentically and can be interpretable to both 'scientist' and 'non-scientist' alike, thereby creating 'sideways' rather than top-down or bottom-up perspectives. This paper is both a methodological paper and a treatise that looks at some of the theory underpinning such approaches, drawing on the theory of citizen or 'bottom-up' stakeholder engagement in science but also co-created engagement, emphasising the learning and trust-building benefits of this 'sideways' engagement. It describes how some established and novel methods (participatory agent-based modelling; co-constructing computer games; and participatory social network mapping), can be used to engage stakeholders in iterative, constructivist communication, allowing researchers and stakeholders to co-create a structured 'reality' separate from the reality it represents. We discuss how such approaches support and contribute to scientific outputs that better represent participants' reality. Our findings show that, when applied to ecosystem services, agricultural adaptation and disaster risk management, such representations provide communication opportunities and spaces for reflection and constructivist learning. The structured outputs allow stakeholders—both participant and researcher—to 'mirror' their human-environmental system to collaboratively think about gaps and problems in understanding.

[1] Stockholm Environment Institute, Oxford, UK. [2] Eurac Research, Bolzano, Italy. [3] Institute of Social and Cultural Anthropology, University of Oxford, Oxford, UK. ✉email: richard.taylor@sei.org

Introduction

Theorists of the public engagement with scientific matters have long emphasised both complexity (Gregory and Miller, 1998: *passim*) and the need for participation (Fuller, 1997). Others deal with the politics of what is going on in such interactions in a wide-ranging manner (Fischer, 2000) or the high-level analysis of tensions between theoretical ideals and practical considerations such as provided by Delgado et al. (2011), who analyse approaches to public engagement in nanotechnology. The science of the environment, and its governance, is both complicated and complex: by 'science' we just mean knowledge (for example, Ziman, 2000); while 'complicated' simply refers to many possibilities within the system, and 'complexity' here relates specifically to issues such as non-linearity, feedback, and the possibility of unintended consequences (for example, Ramalingam et al., 2008), thus better understanding of the scientific issues and their interactions with their constituency—that is the environment itself but also the people who live in and manage that environment—is required. Public policy analysts have referred to these types of issue and their associated problems as "messy" (Ackoff, 1974); "wicked" (Rittel and Webber, 1973; McConnell, 2018); or even "super wicked" (Levin et al., 2012; Forrester et al., 2019a). They also emphasised that a plurality of parties is invested in these problems, being "equally equipped, interested, and/or entitled to judge the solutions" (Rittel and Webber, 1973). Other analysts focus on the greater need for pluralistic 'peer-review' of science knowledge and have advocated wider stakeholder engagement under conditions of "post-normal science" (Funtowicz and Ravetz, 1991; Kasemir et al., 2003; Andersson et al., 2010). This has also on occasion resulted in participatory exercises where 'bottom-up' analyses are cast almost as a critique of the scientific hegemony (Potts, 2004; Wynne, 1996; Yearley, 2000). These analyses also further unpack the relationship of the public or citizen stakeholder (i.e., participants whose primary stake is through being a local resident and knowledge-stakeholder) with and in the production of science.

On the other hand, Rodela et al. (2012) find limited evidence of the involvement of stakeholders in empirical research on social learning in environmental management contexts. They also find that researchers tend not to disclose ontological positions that guide methodological choices. Moreover, researchers frequently move between more than one theoretical or philosophical perspective (Rodela et al., 2012). Different methods might also be creatively combined under different ontological and epistemological positions (Barbrook-Johnson and Carrick, 2021). We suspect that this is increasingly the case in participatory research into human-environmental issues (given the diversity of aims and methods employed—see Moon and Blackman, 2014).

In this context, we believe that there is a pressing need for not just better methodologies for better public engagement but also for a better social science understanding of the theory behind such methodologies: what is the legitimacy of citizen involvement in creating better understanding and how can it be improved. We ask: How do social science theories about interaction, communication and learning between researchers and stakeholders help deepen understanding of practices and methods of participatory engagement, and how can the co-designed outputs help create better science-informed communication? This paper is both a methodological paper and a treatise that examines theory connected to methodology, and thus there are both "what" and "how" research questions.

Our work was originally conceived of as a method to bring about a more active scientific citizenship as a critique of scientific hegemony (Irwin, 1995; Forrester, 1999). In this paper we show how this can be achieved through adaptation of formal methods of representation (maps, models, games—the detailed expressions of which can only be understood by experts) to make them more useful to others—such that a non-expert could recognise in them the complex and messy realities of environmental issues and their problems. Structured output methods involve individual and group exercises where participants engage with co-created outputs to represent and elaborate their views, ideas and beliefs and hence learn together. They are not focus group exercises, interactive workshops, policy dialogues or other meetings that involve consultation or discussion on policies or planning decisions.

The structured output delineates a system that is the subject of the investigation. A minimum requirement for a structured output is that there is an output, which stands alone or apart from that which is being described. Participants are experts and other knowledge stakeholders (often bridging different types of evidence). The perception of and commitment to such an exercise likely depends on the legitimacy of the actor who invites the participants to join (Voinov and Bousquet, 2010). Thus, the initiation and early engagement is important for the later credibility of a process that aims "to build more equity and confidence in a heterogeneous group of people by providing a framework to share knowledge, cultural and traditional principles, access to power and status, ability to communicate and interact" (ibid). We present three examples of structured outputs in this paper. The paper is not, however, a report of those projects but rather a treatise on how and why these approaches are and can be used. We argue that such representations provide communication opportunities, and that our work contributes to the literature on science-informed communication, including that pertaining to environmental risks.

Risk managers and planners face increasingly complex problems (including wickedness and messiness) and difficult choices. Participatory research approaches can help support transdisciplinary/post-normal knowledge production and facilitate useful communication processes in situations where scientific expertise has no hegemony: that is where science advice—and other policy discourses—are necessary voices, but not the only voice. Such situations involve human agency and 'the environment' and can be observed as the interaction between stakeholders or agents and some other 'actor' in the widest Latourian sense (Latour, 2005), but also through "observable events and interactions between people and objects" (Zeitlyn and Just, 2014, p. 9). This includes understanding the process of communication (for example, Fuller, 1997; Jensen and Holliman, 2009) and the interplay between communication, participation, and policy (Collier & Toomey, 1997, 175*ff*).

Participatory methods that produce structured outputs not only generate new empirical evidence, but also allow participants to become better aware of their own context. They allow the creation of a space for reflection, which can help ameliorate the sometimes confrontational nature of some participatory processes, by focusing attention on the created object (i.e., the structured output). Further, the use of a drawn output (for example, Cinderby and Forrester, 2005; Forrester et al., 2015) creates a clear common language often less prone to ambiguity. Furthermore, the use of such structured outputs also helps to unpick and 'map' some of the mess surrounding common human–environmental issues, exploring the range and diversity of beliefs not only of citizen public but also of the officials representing statutory and governmental agencies. Yet, there is a need to better understand how different participatory research methods can support communication and learn about such underlying beliefs, all of which contribute to complexity and wickedness.

The methodologies we are concerned with produce structured outputs that can function as boundary objects. These are entities "shared by several different communities but viewed or used differently by each of them" (Star, 1989). Such objects have "different meanings in different social worlds but their structure is common enough to more than one world to make them recognisable, a means of translation" (Star and Griesemer, 1989). Use of structured outputs of participatory processes as boundary objects helps avoid the problem of having to "infer what must be in their minds" (Bailey, 1991, p. xiv). Their use can operate as a common language to facilitate translation across and between social domains. Further, a boundary object such as a highly structured output can help move the model/created understanding away from being 'simply' a metaphor (Ravetz, 2003) for the real world with the concomitant problems such may bring (Norgaard, 2010). It does this by maintaining a recognised link to known and lived realities on the part of those drawing the object —that is the stakeholders/participants. Furthermore, such 'structured outputs' have the virtue of apparent *precision* and through that precision can be used to clarify understandings that are not easily observable empirically, and are otherwise difficult to elicit (Forrester et al., 2014; Taylor et al., 2014; Forrester et al., 2015; Matin et al., 2015). Thus, communication is facilitated not only through interaction of stakeholders with different understandings but *between the stakeholders and the tool of investigation*, the structured output (see also Forrester et al., 2019b). We argue that this communication would not have taken place to the same degree or at all if these types of approaches had not been employed. The boundary object—if it is representing citizens' own knowledge—also provides a re-framing of what are sometimes otherwise disempowered voices, can help build trust and understanding between different stakeholders.

Methodology

This paper shows how three differing methodologies producing structured outputs have been used, appraises their contribution to participatory projects, and then relates these practical experiences to the relevant theory (about interaction, communication and learning between researchers and stakeholders) outlined above. We investigate participatory applications of agent-based modelling (P-ABM); computer games (P-Games); and participatory social network mapping (P-SNM) in environment and development-focused projects to understand the opportunities offered by each to the facilitation of the communication as well as the elicitation of stakeholder knowledge to the benefit not only of researcher stakeholders and their projects, but also of participant stakeholders and the communities they represent (i.e., both top-down and bottom-up concurrently: what we call a sideways approach). These methods are briefly described using the different projects in which they were initially applied, namely: *Whole Decision-Network Analysis for Coastal Ecosystems* (WD-NACE) on the south Kenya coast; *OxGAME* in Cameroon; and part of the *Building Resilience Amongst Communities in Europe* (emBRACE) project, which took place in Südtirol in northern Italy. This paper argues that to foster better communication of environmental issues using participatory approaches we need methods where the full complexity of understanding might be understood and harnessed. We aim to make methodological contributions to the literature on the beneficial use of multiple methods spanning qualitative and quantitative assessment (for example, Crossley, 2010; Forrester et al., 2015; Mallampalli et al., 2016). Further, we seek to locate these methods within a realist anthropological understanding (Zeitlyn and Just, 2014) of the drivers, motives, and learning outcomes of stakeholders which, we believe, will contribute a strong social science basis for participatory/citizen engagement in environmental and ecological science with lessons that are applicable to science communication more widely.

In this paper we present reflections of researchers involved in these three cases, each of which used different participatory methodologies and each within mixed methods projects, drawing on material collected with stakeholders focusing on whether and how interactive and constructivist communication occurred in the process of using these methods. Each method is different, but all share several important characteristics. Table 1 outlines the projects and the related methods. All projects have a minimal common methodology, which makes them comparable for the purposes of this paper, which may best be summarised as the use of structured outputs for communication and dialogue, and which leverages the communication potential of participatory research methods in various ways. The overall implications of using these types of methodologies are discussed later.

Table 1 shows some relevant data on each of the mixed method projects. All the projects involved multiple stakeholders at a range of levels of environmental governance and thus both provided and facilitated cross-stakeholder communication. The projects also took an inclusive standpoint on who is a participant/stakeholder (Forrester et al., 2008, p. 3); communication was always paramount, with learning tacit or implicit, whether by the researchers or the stakeholders, or both. The final (right-hand side) column describes the main "knowledge production practices" within the project following Rodela et al. (2012: Table 1). The four dimensions/philosophical perspectives are 'positivist': belief that empirical observation informs knowledge production and universal truths; 'interpretive': belief that reality is socially constructed and context-dependent as is the knowledge that actors use to engage with it; 'critical': belief that realities should be understood through the lens of power relations; 'post-normal': belief that knowledge is multifaceted and needs to be validated with extended stakeholder communities (Rodela R et al., 2012; Moon and Blackman, 2014). All projects were interpretative (due to the methodology itself) and two had post-normal elements of learning because of the transdisciplinary nature of the conceptions of the projects. For us, transdisciplinary research interlinks various scientific knowledge production processes with the development of solutions for addressing current societal issues or challenges. Thus, while each project/method incorporated some different assumptions, concepts, and outlooks, which constrains comparative analysis, for the purposes of this paper how research questions are described, and the data and validation aspects of research are standardised with respect to the three methods being described: agent-based modelling; gaming simulations; and participatory social network mapping.

The subjective matter of research spans several areas of environmental research including ecosystem services and development (P-ABM and Games exemplars) and disaster risk management (P-SNM exemplar). Each example deals with stakeholder or citizen engagement in environmental science processes or governance. We describe the main goals as well as the methodological approach in each, and we provide information about the participants. Our focus is upon the beneficial communication outcomes of using structured-output participatory methodologies between researchers and community participants at multiple levels. Each example increases the sum of (scientific) knowledge but also contributes to a wider 'sideways' participatory agenda by increasing and improving both researcher and citizen knowledge and understanding.

P-ABM—the WD-NACE project. The WD-NACE project, piloted participatory agent-based models to help reveal how coastal stakeholders—working individually and within social networks—generate, share, and select knowledge before finally acting upon it. These interactions produce feedbacks that pose challenges to the sustainability of ecosystem provisioning and livelihoods. It was an opportunity for researchers and stakeholders to learn about Ostrom's (1990) 'design principles' for collective management of common pool resources, a seminal theoretical contribution. WD-NACE centred on the South Kenya coast where decentralisation of responsibility had given rise to a new type of village-level management actor called the Beach Management Unit (BMU), with the aim of improving the management of fisheries around reef ecosystems (see King, 2000; Oluoch and Obura, 2009). The WD-NACE case employed a participatory modelling approach (Barreteau et al., 2003; Étienne, 2006). This follows a methodology pioneered by the 'Companion Modelling' group, involving "co-construction of conceptual models that represent visually multiple viewpoints and can be employed as mediating, discursive objects that promote collective learning processes" (see http://www.commod.org). The project worked with BMU members, local government and other coastal community representatives. Workshops, each with around 30 participants, were conducted over three days in two locations: central Mombasa (district governance, BMU representatives and NGOs), and Ukunda (BMU and fisher/fish traders from Msambweni district). Participants shared their economic, social and behavioural data and used this to 'map' the social networks involved in resource decisions. This provided conceptual models of a community's area and of its governance.

The next stage of WD-NACE was to represent the behaviour of actors in 'code' using the NetLogo platform (Wilensky and Rand, 2015), which provided a means to simulate and visualise aspects of fishers' routines. The co-created pilot ABM was then taken back to a second set of 'feedback' workshops. Kenyan fishers, government policymakers and policy advisors were invited to check on how well the ABM matched their experiences or not, to suggest improvements, and to test whether it could be used by them to investigate policies aimed at reducing poverty and managing ecosystems sustainably. This was followed up with the development of further models enabling participants to explore different scenarios informed by coastal stakeholders themselves (see Supplementary Material for details)[1].

Games—OxGame. The goal of OxGAME, a participatory gaming experiment in the Republic of Cameroon, was to create a tool to help an experienced anthropologist discuss future agricultural adaptation strategies with farmers and experts, moving beyond empty platitudes about uncertain futures in ways that allow robust and demonstrable documentation. The project sought ways to access tacit knowledge and generate new knowledge without explicitly asking questions. The computer-based gaming environment indirectly asks questions that the participants address by participating in game-play. In OxGAME, UK-based researchers worked with local researchers to create a simulation of a basic farm ecosystem (soil with fertility that declined when farmed, invading weeds, forest, etc.). The game required players to decide which crops to plant, when, and how much of their farm to plant with what.

The goal was to look after the crops as they grew, harvest them, sell them at a market, and spend any surplus cash after meeting the costs of living. Challenges were also added: invading cows destroying crops; bushfires; illness; and extra mouths to feed. Initial versions of the model were tried by local farmers to calibrate each parameter, for example how long it takes to prepare a hectare of the field for planting; the price range of manioc; how

Table 1 Overview of methods explored in this paper and the projects in which they were used.

Project information					Method information			
Name	Team size	Duration (months)	Main focus	Type of funder	Name	Prior information shared with participants?	Main participants	Main knowledge production practice (following Rodela R et al. (2012))
WD-NACE	≈6	24	(1) Poverty alleviation (2) protecting ecosystem services	Joint UK research councils + government department	P-ABM	no	Local governance agencies; community leaders; and individuals	Largely post-normal/ interpretive (some stakeholders critical)
OxGAME	3	12	Farmers' adaptation to climate change	Academic research fund	Games	no	Local farmers & agriculturists	Interpretative
emBRACE	4	20	(1) Risk governance (2) preparedness and response to landslide events	European Commission research directorate	P-SNM	no	Officials from local administration; risk managers; volunteers from emergency organisations; local residents	Interpretative, critical and post-normal

frequently cows destroy crops; what can be bought with surplus cash; and the cost of different goods. The game also recorded in its log file each decision made by the player. The pilot simulation game was played by six to eight farmers (previously unfamiliar with computers let alone computer-based simulations or games) each morning for 10 days, after which the model was updated with their feedback. The game was introduced in Mambila (the local language) as being 'a game which is like farming': researchers were deliberately non-directive about its goals. The farmers quickly understood the game; one reason may be the highly visual representation of the researchers' understanding which the computer platform allows. The first question asked was always: "what is wrong with this game?" (and by implication, what is wrong with the researchers' understanding). Replies were detailed and often numeric: for example, the number of days it takes a child to clear a hectare was much less than the initial estimate; also, significant details had been omitted such as the fact that picking coffee requires a costly spray to kill venomous ants; and so on. The output is a model that is much more nuanced, including variables that none of anthropologists, local informants when explicitly asked or local agricultural development staff had mentioned as being significant.

P-SNM—the emBRACE project. In what looks on the surface to be a very different case, the authors used social network mapping to investigate the role of community disaster response networks in Südtirol, Italy, as part of the Europe-wide emBRACE project. The importance and the value of social networks are well known (Putnam, 1993; Aldrich, 2008) particularly in preparing for and dealing with disasters by providing access to resources at a critical time, diffusing information among individuals, and creating trustworthiness (Aldrich, 2012). A social network map was constructed through consideration of the actors, the links between them, the attributes of the actors, and boundary conditions of the network determining the inclusion and exclusion of actors (Cumming et al., 2010). The goal was to visualise and better understand the social networks in the immediate response phase to a landslide that happened in the small alpine municipality of Badia in Northern Italy, in particular, to see whether there was any observable difference between the 'official' risk management network and that involved in the response phase immediately after the event (amongst the affected population). In this case, the network map was the structured output of research—where, similar to the ABM and the gaming approaches above, both the process of creating the map and its subsequent employment provided opportunities for communication, learning and engagement between stakeholders. Combining mapping with interviews offered the opportunity to study networks as both structure and process at the same time (Edwards, 2010). Initially, a population survey was conducted, asking residents, which organisations they would contact in case of a landslide happening. The answers of all respondents ($n = 1074$) were visualised in a social network map, which showed significant complexity but also clearly indicated who the key actors were in the minds of the affected population (Pedoth et al., 2019).

In a further complementary step, this data (the community map) was validated and discussed with the identified risk-management actors and a qualitative network mapping exercise was also carried out through individual interviews with them ($n = 10$, on-average one hour discussions) focusing on how, and with whom, they shared information in the aftermath of the disaster. As the starting point of the mapping was a blank sheet of paper, the stakeholder and the researcher were at the same level. This participatory mapping, accompanied by the narratives of the interviewees, allowed a deeper understanding of what is "going on" within the network of emergency responders (Crossley, 2010).

Thus, across the three methods, a first step is that each methodology allows the stakeholders to present data or knowledge to each other, which is then used to co-create the structured output (the map or model); the co-creation of knowledge is one of the main strengths of such an approach. In a second step, both stakeholder and researcher engage with the structured output in a way that allows participants to reflect upon it directly and, on equal terms, have a constructive dialogue. The structured output (aka "mode-2 object" (Nowotny et al., 2001, 147ff; Forrester et al., 2002)) created does not assume a priori that one kind of information or perspective is more important than any other. Participatory mode-2 knowledge production can be thought of as the production of knowledge, which could not have been created by a single expertise (cf. Funtowicz and Ravetz (1991) "post-normal science"). Thus, the 'data' analysed include both qualitative and quantitative; technical scientific information and citizen information; the structured output and participants' reflections upon it; and the authors' reflections on the process as data.

Results and discussion

As this paper sets out to provide a treatise on *how* and *why* these sorts of methodologies are and can be used it does not, therefore, provide full results of those projects per se. Rather, we suggest that drawing upon "the cross-disciplinary nature of drawing as a language"[2] these projects taken together show that representational elements of structured subjective methodologies—especially when considered as boundary objects—allow opportunities for engagement with and learning from stakeholders. We start this section by discussing and comparing results across the 3 projects, in the context of relevant methods and theories. Then we turn our attention to the overall implications for participatory research methodology. The practices we describe of using formal representations to better gather the views, ideas, and beliefs of knowledge stakeholders are not new (see Barreteau et al., 2003; Étienne, 2006). There are also insightful expositions of how and why individual methodologies can be used with stakeholders (for example, Voinov and Bousquet, 2010). Our contribution builds on this work by discussing the merits of structured output methodologies taken together and the differences and similarities in knowledge production practices and communication processes they support. We end this section by highlighting our insights and added value to this literature.

Summarising and comparing results. In our P-ABM example, modelling with stakeholders—such as was used on the South Kenya Coast—helps understand linkages and illustrate dynamic feedback loops at the local level, thus making explicit various facets of complexity. Model demonstrations with stakeholders emphasised the aggregate impacts of changes. For example, the model was used to explore the effect of changing the number of large boats on fisher incomes and on fish stock levels (see Supplementary Material for details). This also helped stakeholders think about ways in which different model outcomes are sensitive to input assumptions. Differences were discussed between two different management scenarios in relation to fisher income: contrasting communal versus private ownership of boats. Participants offered ideas of how to improve the accuracy of the model with respect to issues such as incorporating government regulations concerning illegal fishing gear and suggested connecting the model to weather predictions and sea conditions. At the final workshop of WD-NACE in Kenya, it was agreed that it would be important for resource managers to understand such models and use them as thinking and learning tools. Using computer-based models proved very popular with fishers and other stakeholders, and this improved everyone's understanding of which data are needed, and which feedbacks of the linked system are understood least. From the perspective of the 'recipients' of the original project in Kenya as discussed here—fishers along the south Kenyan coast—that work has continued through several subsequent projects.

Furthermore, our P-ABM case illustrates how a systems approach can facilitate synthesising existing knowledge about ecosystem services—sense-making, or 'making sense' in other words. During the participatory modelling in Kenya, one fisher was reported as saying "Ah, now I understand why KMFRI [the Kenyan Marine & Fisheries Research Institute] are always asking us how many baskets of seagrass we collect". The fisher had not—until prompted to consider the whole ecosystem by modelling it—made the link between undisturbed seagrass availability and its role as a nursery habitat for marine species. He made that link himself through working through the model (one of many models uses; see Epstein, 2008; Taylor et al., 2014, for other suggested uses).

Whilst piloting the participatory games with Cameroonian farmers we used the same *NetLogo* platform as used for the ABMs (in Kenya). However, we found it not well suited for a gaming interface. Unlike ABMs, games seem to work better when they resemble the users' reality, for example with respect to their village and the surrounding farmland. This extra burden of visual representation of details, along with writing data to a log file in order to record players' decisions and trying to capture the screen as a video (using *NetLogo* replay module) meant that performance was an issue. Nonetheless, by the end of the project each player had run through 20 years of game time. The log files were used to discuss and learn why players had taken identifiable strategies. In the game, most players had realised that it was necessary to invest in coffee before moving to palm oil, the profits from which could enable the purchase of the most sought-after luxury items (tin roofs and motorbikes). Discussions focused on why some options were not taken in the game, for example selling products to a market outside of the village: even in a 'game' this option was not taken because in real life the farmers would not trust others to take the food to market and return with the proceeds—signalling that participants were imputing complex real-life factors into their game decisions and actions. The NetLogo source was shared with Cameroonian colleagues (from several Universities in Cameroon) who continue to develop similar approaches; it and the logfiles are available at: https://zenodo.org/record/259340.

Although the use of P-SNM involved a different interface—and a different substantive issue—it allowed similar engagement with and learning from stakeholders acting at different levels of governance (from parochial up to provincial levels), with different roles and responsibilities, and with different levels of expertise (volunteers, officials, and decision-makers). Using different mapping approaches at different steps enabled researchers to gain an outsider view of the network in terms of the structure of the whole network (which could not be seen by any individual actor), but also to gain a perception of the network from an "*insider's* view, including the content, quality and meaning of ties for those involved" (Edwards, 2010). This process, together with the involvement of stakeholders starting from the design of the study and followed by iterative interaction, resulted in a real and reciprocal exchange in contrast to what often is criticised as merely data and knowledge extraction in disaster research (Le De et al., 2015).

However, in this case, the use of P-SNM and the topic of information exchange took place in a milieu often dominated by technical assessment and numerical data. What was observed may be what Spiekermann et al. (2015) describe as different existing types of knowledge and the need to pass from data and information towards knowledge and wisdom. This is well reflected in the quote from an official of the provincial administration:

> We have a lot and probably enough data and information about hazards and risks. What is the challenge now and for the future is to share, communicate and 'activate' this information; how to bring it out to the people and engage with them. This goes beyond our expertise as technicians and we therefore need to include people with different backgrounds and expertise in 'social issues' in order to get a step further in risk management.

The learning exchanges using mapping generated interest that contributed to a follow-up project in Badia and other municipalities (financed by the stakeholders and authorities themselves), and a training course on social research methods for the technicians. Inclusion of different voices in risk management and the use of communication methods better grounded in social science is a way to overcome the limitations of the knowledge deficit model of communication—the idea that what is needed is better information (namely, expert knowledge) and better delivery to close a presumed gap in knowledge. Although reducing ignorance over scientific issues is important, risk communication is usually more complex than this model implies. Moreover, a risk communication process is more likely to be successful when it responds to concerns of the public when it is not seen as a 'one-way' transfer, and "is thus transformed from a means of distributing information to a vehicle for mutual learning and deliberation" (Engdahl and Lidskog, 2014, p. 706).

Structured subjective methodologies, such as social network mapping, agent-based modelling, and 'developments' of computer-based ABMs such as gaming simulations elucidated in this paper excel at representing 'social issues' in different ways. We are ***not*** arguing that computer simulations *on their own* will provide instant solutions to this official's need for a step further. Other methodologies—especially other highly structured methodologies such as Q-methodology (for example, Donner, 2001; Eden et al., 2005; Webler, Danielson and Tuler, 2009; Cuppen et al., 2010; Forrester et al., 2015) and participatory mapping (see the section "Introduction") are useful adjuncts to co-creating knowledge using computer-based simulations.

A key point is that there are subjective criteria to which various stakeholders refer to implicitly. These influence not only individual perceptions but also how ideas are communicated (see Étienne, 2006, Fig. 1). For instance, in our P-SNM case, the activity required participants to state who is part of the network for disaster response and for disaster recovery, and the significance of actors and links (their power, responsibilities, etc.). Throughout, the 'sorting process' necessitated by structuring data allows for—indeed forces—key stakeholders to confront their own personal beliefs in a way not always considered by them within their day-to-day work and often not facilitated by other forms of engagement. It necessitates both researcher and participant to consider their own beliefs and how they 'really understood' the issues (Forrester et al., 2015). The structured way of collecting, representing, and presenting data allowed these findings to become clear in a way that more traditional qualitative methodologies might not.

Implications for participatory research methodology. The three examples show interactive and constructivist communication occurring in a range of settings. In the remainder of this section, we discuss the main *methodological* lessons learnt. Initially, however, it is worth highlighting the fact that these apparently different approaches have two similar underpinnings: firstly, they are all explicitly or implicitly part of the participatory science movement in that they all share a belief that the 'citizen' has something to contribute to the science process (cf. Irwin, 1995; Collier and Toomey, 1997; Jensen and Holliman, 2009) and that these contributions are critical. In other words, they all go beyond simple ideas of democracy; simple economics; and trust; to include the logic of improvement to scientific knowledge itself (cf. Forrester 1999, 320ff). Secondly, they have in common the production of a structured 'reality'—separate and separable from the reality it represents. Such a structured output is both a boundary object and a useful heuristic device allowing learning processes and possibilities not offered in the same way by other participatory methodologies that do not produce such an output.

Thus, the type of methodologies explored in this paper can all be said to 're-frame' stakeholder knowledge to make it interpretable to technical expertise; while vice versa, they can be used to help stakeholders understand technical expertise, and further, they can be used to allow both to explore the lived realities of human–environmental interactions.

When stakeholders see the value of the structured output, and their own role in the process, this contributes to building trust. However, "trust does not develop through information and the uptake of knowledge but through emotional involvement and sense-making" (Engdahl and Lidskog, 2014, p. 703). Trust seems to be created when scientific information is distilled and its essential meaning is agreed upon collectively, often using informal opportunities to do so (Scott and Taylor, 2019, p. 14). Therefore, a process is required beyond 'simple communication' and that process must facilitate making sense of issues. According to Kompridis (2011), possibilities in public policy are a function of the sense-making vocabularies we develop; vocabularies that facilitate and constrain how we interpret issues, communicate possibilities, and contribute to change. We suggest that this overarching approach, and maybe even some of the methods described above, help facilitate making sense of issues. It is more than trust and language: the processes we have described of undertaking 'sideways engagement' mean that stakeholders can legitimately feel an ownership of the maps and models that have been co-produced rather than information being extracted to be processed by experts or produced solely by communities themselves.

Different aspects of the methodology can be adapted to suit the subject of enquiry, the kinds of participants involved and the nature of the interaction. Notably, new technologies can help to make the structured outputs themselves more engaging, and their employment more rigorous. Further, they can contribute to learning (arguably one result of communication) by participants and researchers, non-technical-expert stakeholders, and technical experts. In particular, if we accept that learning can be brought about by acquiring, modifying, reinforcing, or synthesising either existing knowledge or beliefs then we can see that each of the three methods discussed above probably have differing abilities to bring about communication/learning in a different milieu. This suggests not only tailoring participatory methods to suit particular learning requirements but also using suites of methods. So, for example, in the *Borderlands* study on flooding (see Forrester et al., 2015; Bracken et al., 2016) semi-structured interviews were used alongside Q-Methodology and participatory mapping, and in the ABM exemplar described above the ABMs were part of a wider project using interviews, life histories, and social network mapping. The use of ABMs combined with role-playing games for environmental assessment and stakeholder learning has been developed through the 'Companion Modelling' approach (Barreteau et al., 2003; Étienne, 2006). This paper is not advocating any one methodology, so this discussion should be taken holistically. It is further important to remember it reflects usage *in the specific project exemplars described* (see Table 1) although relevance to the wider participatory agenda should be clear: context is important and other applications may differ (e.g., used for extractive or purely science-led engagement). Furthermore, we take no firm line distinguishing between the researcher and the researched when it comes to where learning can and should occur.

Researchers who use and who wish to use bottom-up approaches could reap great benefits from the 'sideways' communicative potential of methods such as we describe, with highly structured outputs, which function as boundary objects, especially those methods that cope well with qualitative as well as quantitative analyses (a.k.a. Q^2). This can be used to better understand complex systems, producing structured outputs, which help to create space for learning and contribute to better outcomes. Multiple and mixed methods can be used to promote increased participation in scientific research and in resource/environmental management. They enable participatory science projects to go beyond a purely scientific literacy agenda (cf. Bonney et al., 2009) and widen participation in scientific knowledge co-creation (cf. Irwin, 1995; Nowotny et al., 2001). This, of course, requires a re-thinking of what is knowledge (cf. Nowotny et al., 2001) and, further, some theory of the citizen's 'social' is required in order to understand better what is happening. The projects above—taken together—show how even "partial" (Zeitlyn, 2009) pictures of 'reality'—if we have enough confidence in those bits we do recognise (see Carpenter et al., 2009)—can be used to start to build better understanding, and thus knowledge, and thus a 'better' citizen-engaged science and through its policy and action.

We argue that for each of the three projects described above, by creating a structured output an appreciation of the 'mess' is created, allowing us to derive a better understanding of the relationship between different parts of human–environmental systems. This is a result of sorting and sense-making processes implicit in the methods. The outputs also facilitate better communication between stakeholders with different or competing understandings of—and engagement with—human–environmental systems and, thus, result in better science (i.e., knowledge). They also address some of the issues related to the complicated nature of the problems inherent in human–environmental systems and the place of these methods within communication—and learning—processes. The primary approach in each case has been to integrate local stakeholder knowledge, provide access to technical data, encourage greater participation in decision making and overall create a dialogue between local stakeholders, planners, environmental modellers, and policymakers with the ultimate aim to improve decision outcomes for local communities (within the context of human–environmental systems). Participation in this sense has a normative as well as a pragmatic focus. Not only is it important that people's voices are heard (cf. Irwin, 1995, Ch. 5), but through using 'maps and models' we argue that people become more fully aware of their context and are able to see how their and others' understanding of the environment overlap or differ.

Modelling also provided a structured way of communication that facilitated co-learning among stakeholders at different levels of decision-taking. For example, the interest and wide range of participants in the ABM pilot project in Kenya exceeded researchers' expectations, and they were able to share knowledge across and within domains with direct resource users, government actors and researchers by using ABMs. Further, the simulation gaming approaches were orientated to generating new knowledge to help address uncertainty associated with climate and other challenges. Another example of this is provided in a discussion of the use of simulation games to make actors think about uncertainty (van Pelt et al., 2015): they conclude "[c]ommunicating uncertainty is thus a delicate task that needs to take into account the opposing discourses about the concept. The simulation game as boundary object fulfils such a role as it allows for communicating about uncertainty without explicitly referring to the concept" (van Pelt et al., 2015, p. 50).

Added value (new insights and confirming existing perspectives). An important insight with producing structured outputs from participatory processes is the way they allow interactive and constructivist communication and learning about emergent issues: this is particularly evident with the agent-based modelling and gaming simulation approaches as these methodologies are designed to work with complexity (Epstein, 1999; Neumann, 2009). Rodela et al. list four possible approaches or 'dimensions of learning' relating to knowledge production: "positivist", "interpretative", "critical" and "post-normal" (2012: Table 1). We suggest a modification, that we might add alongside these the additional dimension of 'generative' learning. This new category covers learning arising from the use of simulation, simulation thus becoming its "most used mode of enquiry" (Rodela et al., 2012).

By making the perspectives underpinning the methodologies clearer, we aim to close the gap between theory and practice. Using suites of methods in different types of combinations is a developing practice, and these practices also frequently address how the representations or outputs of the methods can be understood by participants and by extended peer/peer-review communities as audiences. Our work contributes to this area by investigating the knowledge production practices associated with different structured output methodologies and their implications. We also relate our experiences to the relevant social theories attempting to explain how citizens, managers and researchers communicate and learn about environmental issues. Empirical evidence is required both to develop the ideas and to inspire new applications and further new ideas. It is hoped that this paper provides some foundation to continue that debate. This is required to avoid practice progressing on incomplete or insufficient understanding.

Our work focuses specifically on the outputs of participatory research and their utility when co-design is part of the methodology. We found that structured output methodologies can utilise multiple platforms, switching platforms to re-frame data/knowledge so as to make it easily communicable to—and interpretable by—a new audience. Awareness of audiences and their needs can help tailor which methodology is suitable in any given situation. Some methods look very similar and the differences between them quite subtle. For instance, Games and P-ABM appear to be similar but they fulfil different roles. Games generally rest on relatively fewer assumptions than ABMs. Games make fewer assumptions *because* they leave many decisions to the players (in their responses to the game), while other methods such as P-SNM may involve no a priori assumptions at all. On the other hand, a game may involve repeated tasks that can quickly become mundane and fail to challenge or keep the attention of players. Also, often a game is a simplification of a scientific model (which can be used for validation or for data collection) but in participatory modelling users/stakeholders can also be involved in developing the model. This 'co-construction' or 'co-production'—although time-consuming—allows stakeholders and researchers to collaborate to gain a shared understanding and co-learning can occur.

Use of participatory methods can generate positive feedback from stakeholders involved in the projects, particularly those which used a co-design approach such as in the P-SNM emBRACE case in Italy and the Kenyan modelling studies. In emBRACE, for example, researchers were requested to present their outputs to a broader public within the provincial administration in order to widen the discussion. Based on collaboration and exchange going beyond project life cycles, and requests from stakeholders to undertake further activities together (in Italy and in Kenya), we can confirm that the use of structured outputs can trigger critical discussion and open the door for the acceptance of these types of methods. Where co-design does not happen although communication and co-learning by some may result, the wider uptake of the approach may be slower (see Cook et al., 2016 arguing that there are powerful barriers to the uptake of natural flood management ideas among some policy actors).

Finally, we anticipate the economic and societal impact of these activities can be encouraged even further by promoting structured outputs (boundary objects/mode-2 objects) as seen above and by adopting open data and open source tools where these are available. This latter was also piloted in the case study in Cameroon where repositories containing the structured output and associated data (e.g., log files) were shared, providing an avenue for collaboration, and making learning outcomes observable to other partners.

Conclusion

Across a number of areas where environmental science meets environmental governance, structured output stakeholder engagement methods can help co-create knowledge of human-environmental systems through the co-construction (using processes we call 'sideways engagement') of structured outputs that function as 'boundary objects'. The method of engagement is nuanced and can be considered in its own right as well as its communication and learning potential. It involves knowledge production practices that go beyond a single expertise and unlock different perspectives and potential emerging insights and solutions.

The main ideas that have emerged in practice include the importance of building trust early in the process, treating each participant as equal knowledge contributor and user. In this light an advantage is where critique can be deflected onto the structured output (and on the specifics) rather than the actor. However, trust also needs to be built in the methodology, and as a result in its output. Co-created structured outputs where each participant can recognise their input in the output are useful. Structured outputs can also be employed very effectively as empirical communication tools across levels of governance and between 'citizens', 'managers' and 'scientists'. Bottom-up methods offer the opportunity to get the citizens/local residents' message across, and there is a normative imperative for doing so. In sideways engagement the process is different in that scientists are involved in creating the outputs of the [citizen] engagement. Bringing scientists and stakeholders together and looking sideways—or laterally—at the problem is the first step towards sideways science, that is, a co-created knowledge or a co-created science.

The lessons from these cases using structured outputs leave us in a position where work aimed at understanding complex issues allows us to increase communication and learning about environmental issues. Constructivist learning, based on solid structured communication platforms, employing structured subjective methods can both clarify different positions on the issue and, by activating new knowledge, can augment what each partner can bring to the table.

It has been argued that structured outputs can be used to iteratively compare and re-compare with reality in order to improve our understanding of the latter (Forrester et al., 2019b): this paper rather suggests that such methods produce a structured 'reality'/object separate and separable from the reality, which it purports to represent as a boundary/mode-2 knowledge object and that this 'object' can also be used to both include a bottom-up (citizen) understanding and also to look at the issues 'sideways'. Key is that insight is gained by co-producing a heuristic output and by discussing that output using the highly structured participatory processes described above.

Crucially, so long as the method allows us to co-create an appropriate structured output with stakeholders, this provides the heuristic device and fulfils the criteria we need. We have shown that this process can allow the exploration of many aspects critical to both good environmental science and good governance. These include identifying potentially unhelpful directions of development (avoiding potentially unsustainable, maladaptive, and non-resilient futures). The highly structured outputs (be it model; game; or map) allows stakeholders and researchers to clarify and talk across disciplinary and sectoral 'silos' (e.g., about defining and visualising system boundaries) and they also foster critical reflection amongst stakeholders.

We conclude by answering the last part of our introduction's question first: the outputs work as boundary objects to facilitate sense-making across different groups of stakeholders on the substantive issues and reciprocal communication between technical and local expertise. This requires continued adaptation of the methods and practices (e.g., data produced and platforms used) and potentially diversifying the philosophical/theoretical frameworks applied; researchers do need to think about the theoretical implications of how the methods are used. When these issues are addressed, the outputs can be used with greater legitimacy to communicate and justify standpoints, and allow stakeholders to create mirrors of their systems that can be used collaboratively to communicate and think better about gaps, problems, and come up with new strategies for adaptive governance of—and learning about—the environment.

Data availability

One dataset generated in emBRACE is not publicly available due to confidentiality of the respondents' information. Further datasets are from model simulations and the codes are available. Other data from the 3 projects including workshop reports and other data gathered for the research are available from the corresponding author upon reasonable request.

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Notes

1 Links to model codes are available: NetLogo model codes are at: http://modelingcommons.org/browse/one_model/3435; Modelling4all model codes: http://m.modelling4all.org/m/?frozen=tB3AfKKQQMU_z2Uxm2E14f&MforAllModel=1.

2 an ideal inspired by the artist Tania Kovats, speaking on *Start the Week* on BBCRadio4, 9th December, 2019.

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Competing interests

The authors declare no competing interests.

Ethical approval

Approval was obtained from the University of Oxford School of Anthropology and Museum Ethnography Research Ethics Committee for OxGAME. emBRACE and WD-NACE were both carried out with the ethical approval of the Environment Department at the University of York as well as that of the relevant funding agencies.

Informed consent

Informed consent was obtained from all participants. In the case of OxGAME this was done orally in the Mambila language (Ju Bà).

Additional information

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Correspondence and requests for materials should be addressed to Richard Taylor.

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