Mental models, communication and engagement in marine projects

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Abstract

In a hypothetical decision-making situation in which a unique truth exists and each party's aim in acquiring knowledge is to approach the truth, argumentation would be unnecessary because the best scientific theory would win the argument. Likewise, if truth is irrelevant and a perfect persuasion method is available, argumentation would also be pointless, because arguing parties, each possessing the perfect recipe, would lead a third party to switch sides endlessly. In the real world, argumentation matters because a unique truth rarely exists, information can be uncertain or vague, aims are often ambiguous if not contradictory, and acquiring knowledge can have other purposes besides approaching the truth. Marine scientists are increasingly expected to contribute to complex decision-making by providing not only scientific evidence, but also impact in the form of effective communication and persuasion. Here we review insights from different disciplines on how humans organise knowledge, beliefs, opinions, assumptions and worldviews, how these interrelate and how they affect decision-making as well as the reception of information. By focussing on the theory of mental models and the Causal Layered Analysis we also show how the structure underlying the organisation of scientific and non-scientific knowledge can be reduced to a fairly common framework. We conclude by reviewing some tools a marine scientist can employ in a stakeholder engagement process in order to better understand the audience to which scientific information needs to be delivered.

Keywords: Mental Models; Causal Layered Analysis; Cognition; Individual Transferable Quotas; Stakeholder engagement; Science communication

1 Introduction

Acknowledging that managing a natural resource is fundamentally about managing how people interact with it implies that, besides expertise in ecological and biological processes, marine scientists also need a reasonable understanding of the psychological and social drivers which underlay humans' interaction with the natural environment, their reception of scientific information and their collective decision-making processes. Each of these tasks requires different levels of sophistication in the understanding of human nature. For a model developer, this may be as simple as defining some rules for an artificial fleet in an Agent Based Model of resource exploitation. For a marine scientist involved in stakeholder and community engagement, it may be necessary to understand how different aspects of the stakeholders' attitudes, needs and expectations affect their reception of scientific information. But an even deeper level of understanding is needed when it comes to fostering behavioural change, by affecting either policy or patterns of resource exploitation.

We share a joke in our labs which goes more or less like this. Sooner or later a natural scientist will come to the realisation that humans do not behave as (s)he believes they should: real fishers do not follow the same rules as virtual ones, stakeholders may not understand scientific information as presented, decision makers do not change opinion simply because a scientific report suggests they should. The joke is that when this happens, the natural scientist will conclude that there must be something wrong with *people*. At that point, the help of a social scientist is sought. Naturally, the social scientist cannot quickly fix the problem, rather will highlight the complexity of the problem and the vast literature informing the issue. At that point the natural scientist will conclude that there must be something wrong with *social scientists*. Underlying the joke is the reality that social processes are at least as complex as ecological ones and the cognitive psychology and social cognition literatures are as vast as the ecological literature and, as a result, a marine scientist's familiarisation with psychological and social processes will be neither easy nor quick.

The purpose of this review is to provide a first step towards such a familiarisation. It focuses on two frameworks: the concept of mental models (Jones et al., 2011a) and the Causal Layered Analysis (Inayatullah, 1998; Inayatullah, 2004b; Inayatullah, 2004a). The first has been chosen because a natural scientist may find its meaning particularly intuitive, while the latter helps clarifying how beliefs, opinions and actions can be understood as arising from the interplay of drivers at different cognitive depths. To make this review clearer, we relate these two frameworks to an issue relevant to marine resource management: whether Individual Transferable Quota (ITQs) contribute to environmental sustainability. To clarify, we do not address this specific question here (a review of arguments for and against ITQs' contribution to environmental stewardship can be found in (van Putten et al., 2014)). Rather, we use Individual Transferable Quota as an example and we discuss how the concepts of mental models and the Causal Layered Analysis may help elucidate the views which may be encountered in stakeholder workshops and facilitate communication on subjects beyond the specifics of ITQ discussions.

2 Mental Models

The core idea behind the concept of mental models is that the interaction between an individual and the real world is mediated by a mental representation which is used to simplify ~~and summarise~~ our understanding of how the world functions, to filter information by focussing on relevant components and to test available behaviours (via mental simulation including counterfactual) before turning them into action. While the literature generally agrees on this broad view, ~~various~~ disciplines differ on how they describe the content and form of the mental representation, the functioning of the mental model, the role the mental model plays in determining beliefs and behaviours and the extent to which these mental representations are consciously accessible. These disciplinary differences can be mapped broadly into three dimensions: i) the content and form of the mental model, ii) where the mental model resides and iii) what exactly it is used for. Differences with regard to content and form range from a computer science analogue of an action-perception loop driven by Bayesian inference (Hohwy, 2013) to little more than a collection of images and analogies (Leiserowitz, 2006). On the second dimension, mental models can be thought of as residing in an individual's mind, as distributed among a team of cooperating individuals or more broadly as culturally shared tools and beliefs. Finally, the functional role of mental models can be understood as achieving accurate predictions or reinforcing social cohesion (see Identity-Protection Cognition Thesis below). Useful reviews can be found in (Norman, 1987; Greca and Moreira, 2000; Jones et al., 2011b). Here we describe these different interpretations while discussing how mental models can be relevant to our hypothetical example of managing a fishery via ITQs.

A number of researchers consider mental models as tools for system understanding (Endsley, 1995; Rouse & Morris, 1986) (Craik, 1967; Johnson-Laird, Khemlani, & Goodwin, 2015), that is, simplified versions of the external world which can be used to describe a system, explain how it works, predict its behaviour and simulate the outcome of human interactions with the system. While the term 'system understanding' may convey the perception of accuracy and complexity, there is no assumption that the mental model should be 'correct', in the sense of faithfully represent the real system. Rather mental models are understood to be inaccurate and incomplete (often they are 'wrong' and over simplified versions of reality) and to lead to errors of reasoning (and thus mistaken predictions) which are both fairly well understood and predictable (Dorner, 1996; Moxnes, 1998a; Moxnes, 2000a; Sweeney and Sterman, 2000; Halford et al., 2005; Moxnes and Saysel, 2009). According to this view, a mental model of an ITQ system may look similar to a causal diagram in which regulations, market incentives or social norms lead to different human responses and different economic and environmental outcomes. How sophisticated this mental representation is may depend on background knowledge and the cognitive effort the subject is willing to invest in this task and previous exposure to the issue. While the mental model may be incorrect and incomplete, the *functional* role of a mental model is to carry out an accurate prediction. In other words, under this view a 'good' mental model is one which leads to an accurate prediction.

A different view of mental models is provided by the Identity-Protection Cognition Thesis rooted in the social psychology literature. While structurally a mental model may still appear to describe a real system, to include causal relations and to lead to predictions, the *functional* role of the mental model is no longer an accurate prediction, rather to ensure, confirm or reinforce social cohesion. In other words, a mental model is understood and employed as a symbol of group membership. What matters is how a mental model's components, assumptions and implications (including predictions) are likely to be endorsed by peers (in-groups) and work as demarcation towards competing views (out-groups). Accurate prediction is secondary and at times irrelevant. This theory has been studied extensively in debates on climate change, vaccination and genetic modified food, which have escaped the scientific discourse to enter the ideological arena (Heath and Gifford, 2006; Feygina et al., 2010; Kahan et al., 2010; Jost and Amodio, 2012; Kahan, 2013). Underlying ITQ decisions are issues which could make them subject to similar debates. For example, a mental model of ITQs could switch from a) a description of how different drivers of human behaviour impact environmental sustainability (outcome based) to b) which drivers of human behaviour *should* be reinforced and whether environmental sustainability *should* matter at all (moral/ideology based). The outcome vs ideology distinction seems obvious but in real world decision-making processes the boundaries are blurred and at times difficult to recognise even by the best intentioned players.

Just like images, stories and narratives can also be interpreted as mental models for three reasons. First, stories share many components with features discussed above in relation to mental models: they usually include actors, causal relations, motivations and outcomes. Second, tools are available to interpret stories in these frameworks (Franzosi, 1998; Franzosi et al., 2013) and third a large literature is available on narrative analysis in environmental issues (Hajer, 1995; Dryzek, 1997; Urhammer and Ropke, 2013). In our ITQs example, a story may include the real or imaginary experience of a quota owner or of a fisher left out from quota allocation or of a fishery manager, internal *stake*holder or external *share*holder. The story may include stereotyped description of winners or losers from different ITQ arrangements as well as the motivations driving 'bad' vs 'good' players which may reveal perceived natural and social drivers of the system.

Unlike the literature described so far, Socially Situated Cognition theory views mental models as not necessarily 'located' in our heads, but distributed among different people and the environment, through the use of tools designed to store and communicate information like books, newspapers and the internet. As a result, cognition is understood as embodied in our brains as much as in our sensorimotor abilities and the environment and action emerges from the interaction between an agent and the environment (Jones, 2012; Smith & Semin, 2004). While also rooted in the social psychology literature, this approach has clear links with the concept of stigmergy in ecology (Mittal, 2013) and of perception-action loop in robotics, information theory and computational neuroscience (Cutsuridis, 2013; Hohwy, 2013). Coming to our marine resource management issue, someone expected to provide an opinion on the viability of ITQs does not need to hold a mental model of how ITQs work, but rather may access and 'borrow' one by consulting the literature, the media or peers.

While the Socially Situated Cognition theory focuses on mental models available to subjects who are not necessarily working together or sharing a collective goal, the theory of Team Mental Models (Klimoski and Mohammed, 1994; Mohammed et al., 2010) refers to situations in which people need to coordinate their actions. It explores the extent to which agreement between the mental models of different individuals improves team performance. The topic of team cognition and dynamics is complex and beyond the scope of this review. Relevant to our discussion however is the importance of being aware of the mental models of other team members. This highlights the recursive nature of mental models: just like a decision maker can have a mental model of a management issue, a stakeholder can hold a mental model of the decision maker's mental model of the issue. Importantly, the two may differ (Leviston et al., 2013). Communication and engagement will inevitably be affected by these mental models and potentially distorted by misalignments. Awareness and clarifications of each party's mental model can foster coordination, reduce the need for information exchange and diminish the risk of misunderstandings.

3 Causal Layered Analysis

The Causal Layered Analysis (Inayatullah, 1998; Inayatullah, 2004b; Inayatullah, 2004a), takes its name from the attempt to understand how beliefs, opinions, interpretations, attitudes and assumptions about an issue may be characterised by different levels of conceptual or cognitive depth and different levels of representational complexity, ranging from images and narratives, to technical explanations and deeply seated worldviews. In particular, it suggests that such an analysis should be carried out at four levels. The first level includes litanies, which are brief statements, stereotypes or vignettes, which may be heard in casual conversations or from the news and may spread via social media. They are rarely original, in the sense that they are rarely created or composed on the spot, rather they usually belong to the public discourse from where they can be 'borrowed' when the need arises, just like described by the Socially Situated Cognition theory of mental models. In our ITQ and sustainability example, a litany supporting the establishment of ITQs may sound something like '*people take better care of what they own'* or '*if something belongs to you, you would not trash it'*. Two people engaged in a conversation about ITQs who realise they are in agreement may not need to discuss the issue further. If agreement was lacking, or the meaning of the litany needed reinforcement, then the discussion could proceed to the second level of the Causal Layered Analysis (social causation). This includes technical explanations, rational arguments or mental models which may be used to provide support for a chosen litany. In the ITQ example, this may consist of a reference to the 'tragedy of the commons' (Hardin, 1968) or to studies showing that ITQs can promote economic efficiency (Grafton et al., 1996; Hannesson, 1996) or more explicit mental models as described in Section 2.

Real world issues rarely offer themselves to a clear, unique interpretation. Often, several competing conclusions could legitimately be drawn from the same evidence. In the applied mathematics language, real world issues are almost always underdetermined. Someone may not believe that ITQs improve sustainability. (S)he could retort that '*if you own a quota, you may have an economic incentive to trash it and cash it out now, rather than conserving it*' and may support this litany by mentioning studies which failed to find evidence for ITQs' ecological benefits (Costello et al., 2008). So given that competing litanies and explanations are almost always available and conclusive evidence rarely is, how do we come to prefer one argument over another? An individual's preferences tend to be fairly consistent between different domains (someone supporting ITQs in a fishery is likely to support privatisation in other domains) suggesting that these preferences are not random but share a common root. According to the Causal Layered Analysis this can be found at the third level (discourse/worldview) which includes deeper ideological assumptions and worldviews. These are the subject of much work in the social cognition literature which has been popularised in the climate change debate by showing how in several English speaking countries lack of belief in the anthropogenic causes of climate change is largely determined by political ideology (Heath, 2006; Feygina et al., 2010; Bain et al., 2015). To see how this may relate to the ITQs issue, we employ Cultural Theory (Douglas, 1985; Dake, 1991; Dake, 1992; O'Riordan and Jordan, 1999; Steg and Sievers, 2000; Price et al., 2014b) as an example. Based on both empirical and theoretical work, Cultural Theory describes three preferences for ways to manage Society and Nature: 'hierarchical' (focused on top-down regulations), 'individualistic' (focused on individual freedoms) and 'egalitarian' (focussed on bottom-up local institutions), plus a fourth 'fatalistic' view which sees social order as illusory. Each of these preferences underlies a different worldview about Society and Nature and, most important, how these relate to each other. The 'hierarchical' worldview sees humans as flawed but potentially improvable by social institutions and Nature as able to sustain exploitation only within limits imposed by regulations. The 'individualistic' worldview sees humans as self-serving, ambitious and competitive and Nature as able to sustain essentially unlimited exploitation, allowing for the individual freedom of pursuing an essentially unlimited exploitation under market-driven initiatives. The 'egalitarian' worldview sees humans as altruistic and Nature as fragile to any sort of exploitation, whose protection requires fundamental moral and social change (we refer the reader to (Price et al., 2014a) for an extensive and critical discussion of this literature). It is not difficult to cast opinions for and against ITQs within a Cultural Theory framework. '*People take better care of what they own'* is aligned with an individualistic view of human nature and sees environmental sustainability as a natural outcome (and thus secondary to) individual enterprise and economic incentives. '*If you own a quota, you may have an economic incentive in trashing it and cash it out now, rather than conserving it*' clearly reflects mistrust of individual self-interest and of delegating environmental sustainability to the consequences of market forces and may favour constraints on human enterprise either as formal regulations or social norms.

The analysis above is only an example, and at best reflects a correlation between worldviews and preferences for and against ITQs, not a one-to-one relation. Nevertheless, it helps highlight a further important point: relations between litanies (level one in the Causal Layered Analysis) and worldviews (level three in the Causal Layered Analysis) do not necessarily need to be mediated by rational explanations (level two in the Causal Layered Analysis). Rational explanations may be called in, if needed, but are not essential to develop an attitude towards an issue. Furthermore, while rational explanations may be used to check the validity or consistency of a statement, at times they can be used retrospectively to justify a pre-determined preference, a process referred to as 'motivated reasoning' (Kunda, 1990; Nisbet and Markowitz, 2015).

The fourth layer of the Causal Layer Analysis includes deeper beliefs, including mythological ones, which are culturally shared and rarely questioned. They usually come to the fore when different cultures need to interact. For example, managing a fishery under economic or sustainability considerations may be inconceivable to a culture which sees Nature as a mother figure, deserving unconditional respect. We do not discuss this layer further in this review.

4 From theory to practice

4.1 Eliciting mental models

The ideas discussed so far can be brought into scientific projects via practical methods, which can be used to gain insights into the knowledge, assumptions, attitudes and motivations of a project's team, including both stakeholders and scientists. For example, several methodologies exist to elicit or infer mental models in a laboratory or workshop session. Some of these methods are based on drawing diagrams of relations between events, processes, players or variables deemed to be significant~~ to the problem at hand~~. Depending on the disciplines, these are usually referred to as cognitive maps, conceptual models, causal diagrams or mental maps. Approaches differ depending on whether the content of the cognitive map is elicited via interview (Schaffernicht & Grösser, 2014), text analysis (Carley & Palmquist, 1992) or a combination of both (Seel, Ifenthaler, & Pirnay-Dummer, 2009), whether causation is revealed via direct links or by temporal ordering of events (Doyle, 1998) and whether the content of the cognitive map is provided by the subject (Checkland and Poulter, 2010) (Carley & Palmquist, 1992) or by the experimenter for the subject to process (Van Exel & De Graaf, 2005).

Obtaining a conceptual model as the output of a mental model elicitation effort is likely to be appealing to a natural scientist, since often this is how natural scientists represent theories and scientific models. Ideally, a 'good' conceptual model can be used as a starting point for system dynamic analysis or for developing a more complex computational model. In reality things are rarely so easy. In system dynamics, nodes and links system states- transitions pairings. This is not necessarily what a conceptual model from an elicitation process may include, unless this is pre-imposed by the experimenter, potentially biasing the elicitation itself. Experience shows that a considerable effort may be necessary to translate a mental model into something resembling a scientific model but this translation can be beneficial to all parties in bridging gaps in communication and assumptions.

4.2 Testing mental models

A different approach to assessing mental models relies on bypassing their elicitation, by focussing on testing their performance, under the assumption that the functional role of a mental model is to achieve accurate predictions. A test which assess the understanding of the relation between CO_2 emissions and sequestration for climate change (Sterman, 2008) has been widely replicated and it is known that a large majority of responders fail at what appears to be a very simple decision-making task. This is purportedly interpreted as suggesting that most members of the general public hold mental models of climate change dynamics, which are ‘not correct’ or at least lead to wrong predictions of the outcome of mitigation initiatives. This can be used effectively within a workshop session to reinforce the role that scientific theories and numerical models can play in testing interventions even in apparently simple problems (Boschetti et al., 2011; Boschetti et al., 2012). Similar approaches related to the management of marine natural resources are discussed in (Moxnes, 1998b; Moxnes, 2000b) while an approach involving a more complex model and a more complex elicitation method is discussed in (Richert et al., 2016).

4.3 Analysing cognitive styles and worldviews

Besides eliciting and testing mental models, it is possible to collect information about cognitive styles, beliefs and opinions of stakeholders and the general public at large, using the Causal Layered Analysis to guide both the data collection and interpretation. In (Boschetti et al., 2012) we describe a questionnaire which can be used to study cognitive styles, worldviews, political ideology and attitudes towards complexity, science and computer modelling in stakeholders of environmental projects involving the use of computer modelling. The questionnaire could be used early in a project to understand the type of audience the modelling results need to be communicated to and to design the communication and engagement process. We tested the questionnaire with a representative sample of the Australian population to establish a baseline for comparison and then with a stakeholder team involved in the management of a regional fishery to assess to what extent our stakeholders’ views were aligned with the general public.

In addition, in the Supplementary Material we include a toolkit for assessing the appropriateness of mental models and their relation to the Causal Layered Analysis which includes two tools which can be used in a workshop setting: i) a figure which summarises the concepts we reviewed above and highlights their relations and ii) a checklist of questions we may want to ask ourselves in order to cultivate an awareness of the cognitive styles, attitudes, assumptions and expectations we and our collaborators bring to the discussion table. The purpose of the checklist is to help us focus on *how,* not *what,* we think and decide.

4.4 Mental models, cognitive styles and temporal scales

Because the output of ecological models employed in marine applications often need to be projected several years or decades into the future, in (Boschetti et al., 2016) we studied the cognitive styles involved in dealing with temporal scales so different from everyday life. By using a specifically designed questionnaire, we obtained a striking result. The very act of spending 15-20 minutes answering questions about the future significantly changed the perception of future time horizon (how far the future is from us) and future concerns (what future issues matter the most). There are a number of reasons why using this questionnaire in a project may be useful. Imagine you start a stakeholder workshop and your stakeholders’ initial future time horizon is ~12 years from now (as the literature suggests) and their priorities focus on personal enjoinment, wealth and health (as the literature suggests). Now imagine the workshop addresses the project’s future implications and in less than half an hour your stakeholders’ future time horizon is ~24 years and their priorities shifted to science, selfimprovement and environmental conservation and no one in the workshop is aware of the change. This is exactly the shift we detected in our empirical work (Boschetti et al., 2016). Employing this questionnaire early in a workshop and discussing the results in a team setting can help make this shift known and discuss its implications and significance.

An equally striking result pertaining to attitudes towards the future is described in (Richert et al., 2016). We used an online questionnaire to elicit mental models of climate change among members of the general public and to ask them to ‘run’ these mental models in order to predict the long term consequence of their preferred mitigation policies. We then used a computational model described in (Boschetti, 2012) to test the dynamical consistency of these mental models and a questionnaire exploring cognitive styles, political ideology and general attitudes towards the future. Our results suggest that no *single* mental model describes how our respondents relate the understanding of the climate change issue to future warming. Rather two mental models are needed, one describing how the system works today and which policy choices are preferred (correlated to political ideology and worldviews) and one describing how the system will work in the future (correlated to more abstract attitudes toward the future). When decisions fail to properly account for future outcomes, usually we assume this is due to poor system understanding or short-sighted incentives. Our results suggest that other cognitive limitations may be at play and suggest that it is important to understand to what extent a similar process may occur in policy making in the marine environment, which can be done by using a similar approach. Conclusions

Both the theory of mental models and the Causal Layered Analysis aim to come to terms with the role that rational explanations, stories, perceptions, ideology and social context play in our understanding of reality, our preferences and ultimately our choices. In our opinion, the fundamental contribution these two theories provide to a marine scientist, consist of showing that causation *within our belief system* is neither unique nor unidirectional. This is particularly true for rational explanations which are supposed to be scientists’ foremost tool of the trade and, at least in principle, their core contribution to decision-making. To what extent rational explanations, or mental models understood as system understanding, i) filter the litanies we support by ensuring logical and empirical consistency, ii) filter the data and observations we pay attention to by ensuring consistency with the litanies, iii) filter our beliefs by ensuring consistency with our peers or iv) are chosen to justify our litanies to ensure we project a consistent and rational version of ourselves, is probably a function of context as well as personality types. Ultimately, this is at the root of whether the most effective path to communication of scientific information and persuasion in terms of policy-making or behavioural change is through more accurate mental models, more convincing rational explanations, more appealing litanies or by questioning deeper assumptions.

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more accurate mental models, more convincing rational explanations, more appealing litanies or by questioning deeper assumptions.

6 Supplementary material

A 'Toolkit for assessing the appropriateness of mental models' is available as Supplementary Material at ICESJMS online.

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Mental models, communication and engagement in marine projects, Supplementary Material:

Toolkit for assessing the appropriateness of mental models

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As mentioned in Section 2 of the main text, some researchers consider something as technical as analogues of scientific theories (Chi, Slotta, & De Leeuw, 1994; Doyle & Ford, 1998; Grösser & Schaffernicht, 2012) or as vague as an image or a narrative (Leiserowitz, 2006) as mental models. One might ask what type of mental model would be appropriate given a specific task. Is it enough to contribute to an ITQ decision process by holding to a narrative of ITQ debates, or is a fully-fledged conceptual model needed? This is a difficult question since in general no exact recipe to reach a correct solution is available in complex environmental problems. On the other hand, this does not mean that all available approaches are equally valid, useful or acceptable. This is particularly true when dealing with scientific (i.e. sound, peer-reviewed and reproducible) advice for policy decisions. In addition, policy making is fundamentally about *intervening* in a *system* to achieve a goal. In human cognition, intervention and causal understanding are inextricably connected (Pearl, 2003) and causal understanding is necessary in order to imagine the counterfactuals, alternative scenarios and alternative system states which are the currency of decision-making. It thus seems reasonable to suggest that for a mental model to be appropriate for complex environmental decision-making, a minimal requirement is that it includes the concepts of system and causation, in whatever form is suitable to a particular individual's cognitive style.

One might ask whether similar guidelines can be developed on the most appropriate ways to navigate the Causal Layered Analysis framework. We doubt such guidelines could be provided and focus instead on specific behavioural attributes, habits and cognitive styles, which can be brought to the task. A vast literature has studied the thinking dispositions that help address complex tasks (Dorner, 1996; Stanovich and West, 1998b; Kahneman, 2011). Besides technical knowledge and IQ, this literature focuses on the disposition to spend effort and time on the task, to objectively weigh evidence against currently held beliefs and to consider alternative opinions (Baron, 1985; Dorner, 1996; Kruglanski and Webster, 1996; Stanovich and West, 1998a; Tetlock, 2005). Particular emphasis is placed on self-reflection and self-awareness and on critically assessing our own mental process. In other words, it is important to *think about the way we think* (Dorner, 1996; Tetlock, 2005). With this approach in mind, this Supplementary Material includes two tools which can be used in a workshop setting. The first tool, Figure 1, summarises the concepts we reviewed in the main text and highlights their relations. Its purpose is to help reminding ourselves of what processes may be at play in the workshop setting and monitor their possible occurrence. The second tool consists of a checklist of questions we may want to ask ourselves in order to cultivate an awareness of the cognitive styles, attitudes, assumptions and expectations we and our collaborators bring to the discussion table. The purpose of the checklist is to help us focus on *how,* not *what,* we think and decide.

Figure 1a describes how the 'real world' produces a vast amount of events or facts, most of which are not accessible because of our cognitive limitations. A small fraction of these are turned into *observations* and become accessible. An even smaller fraction is turned into *information* which is actively processed and often publicly shared. What events are filtered into observations and further filtered into information and to what extent a mental model is the ultimate locus of the filtering process, or whether this also includes worldviews or preference for specific litanies has been discussed in Section 3 in the main text.

The column on the left of Figure 1 summarises the concept of mental model. Panel b captures the view of mental model from an individual's perspective (mental representation, system understanding and Identity-Protection Cognition Thesis) with arrow a_4 reflecting the use of mental models to consider counterfactuals and alternative possible outcomes for decision-making. As an example of self-reflection, here we may ask ourselves to what extent we are aware of our own mental model of, for example, the ITQs issue under discussion. In particular, we could ask ourselves:

- Would we be able to describe our mental model to others?
- What does it include?
- Does it include a system, an image or a story?
- If it is a system, can I define the system boundary (what is inside or outside the system)?
- Does it include causal paths for intervention? This can be checked, for example, by asking whether the mental model allows for multiple counter-factual, multiple scenarios, multiple possible system behaviours and different outcomes, or whether it describes a single unique series of events.

Figure 1c represents mental models as distributed between the human brain, the environment and cultural artefacts according to the Socially Situated Cognition theory. Here self-reflection may involve asking:

- Where does my mental model come from?
- Can I trust my sources?
- Am I critically assessing the model? Or am influenced by peer-pressure?

These questions are significant because the vast majority of our mental models are inherited rather than built from information or data. Even scientists, outside their own narrow empirical work, mostly rely on information from the scientific literature and thus necessarily rely on trusting the scientific establishment. In this context, self-reflection may also be needed to ask ourselves about the functional role of our mental model:

- Are we aiming for accurate system understanding and prediction?
- Or are we giving priority to social and disciplinary acceptance as suggested by the Identity-Protection Cognition Thesis?

Further down, Figure 1d represents the concept of Team Mental Model. Here it may be useful to reflect on what mental models our colleagues may hold:

- Do I know my colleagues' mental models? Are they similar to ours?
- Should I check how similar they are to mine?
- May they be so similar as to prevent us from considering alternative understandings?
- May they be so dissimilar as to prevent us from reaching a shared understanding?
- Is it worthwhile to check and gently probe the assumptions of each other's mental models?

The middle column in Figure 1 represents the Causal Layered Analysis framework. Arrow a_5 represents the link between mental models and the second layer (social causation) of the Causal Layered Analysis, which is justified, as discussed above, by focusing on mental models understood as system representations. Arrow a_6 shows how worldviews and ideology may filter the litanies we subscribe to, which in turn can reinforce our worldviews, potentially bypassing rational explanations at the second level. Arrows a_7 and a_8 depict how both worldviews and litanies can affect mental models, while the extent to which mental models can filter worldviews and litanies is less certain. Self-reflection here may involve asking ourselves whether we fully appreciate the implications of the litanies we support or the ideology and worldviews they may reflect. Since we are all at risk of motivated reasoning, we may also ask ourselves whether our mental models have been chosen a posteriori to match predetermined preferences or whether we are using them critically to judge the relevance and appropriateness of such preferences.

- Am I aware of the implications of the litanies I use?
- Am I aware of their underlying assumptions and ideology?
- Do my rational explanations reflect a coherent and consistent mental model?
- Am I aware of how my ideology affects my opinion?
- Have I chosen a mental model to fit my preference?

Finally, on the right hand side of Figure 1, the Numerical Modelling column summarises the hypothetical working of a marine scientist who is asked to develop a numerical model of a fishery subject to ITQs. We can suppose that the modeller needs to calibrate the model with real data and simulate resource exploitation by estimating likely economic and environmental outcomes (arrow a_3). The modeller needs to decide what observations should be used to calibrate the model. This choice is determined not only by the observations' information content, but also by practical constraints, like what monitoring system is available and how the observations can be turned into useful numerical input for the models. The latter depends on what model is used, which in turn is determined not only by the scientific soundness, but also by resource availability and the scientist's computing background (arrow a_9). The modeller also needs to select algorithms describing the behaviour of the resource as well as of the quota owner. There are many techniques available; for example individual vessels could be modelled as agents (as in ABM) or their aggregate behaviour could be modelled by closed form differential equations (or anything in between). Sometimes the choice is determined by the specific scientific question, while at other times the modeller expertise may take priority (arrow a_{10}). This expertise may in turn depend on the academic background (computer science vs maths vs ecology, arrow a_{11}). Once the model results are generated, they need to be interpreted and it is likely that the interpretation (at times in the form of a story) is influenced by the model's technical features just mentioned. This is only a caricature of course, but it does include some very pragmatic aspects of the working life of some marine scientists (see (Brennan and Valcic, 2012) for a pertinent example). More important, this caricature can be framed in a fashion comparable to the Causal Layer Analysis (see similarity between the grey and pink boxes in Figure 1), highlighting the similarities between the development and nature of scientific models and general mental models.

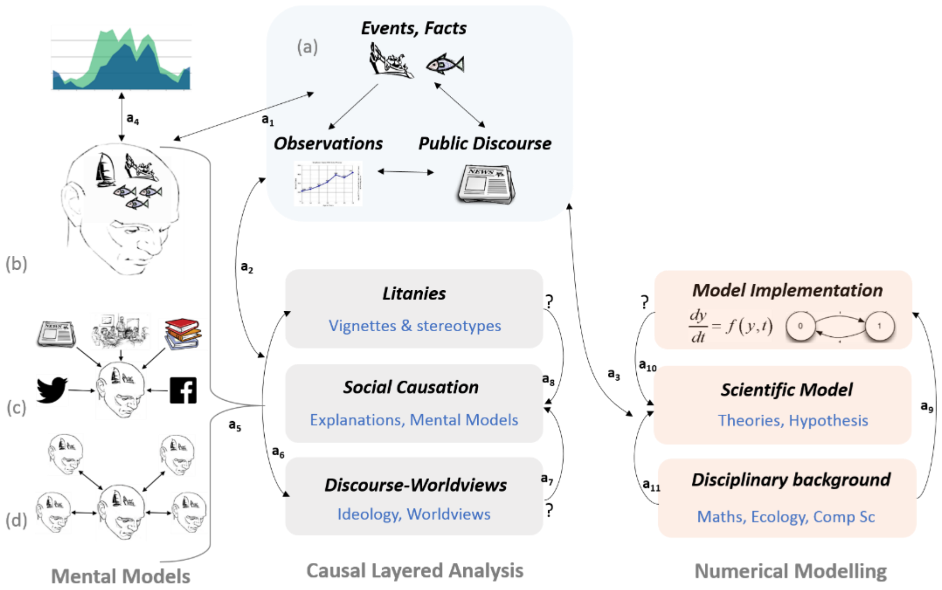

Figure 1. A unified framework of the concepts introduced in the main text and their interactions. On the left hand side we find the different views of mental models. In the middle column (grey boxes) is the Causal Layered Analysis and the relation among the three layers discussed in Section 3 (arrows describe directionality of influence and '?' describe uncertain influences). Both mental models and the layers of the Causal Layered Analysis are influenced by events and observations from the real world (top

panel ‘a’), but also influence which events are observed and how they are perceived. On the right hand side (pink boxes) we show how scientific thinking and the everyday working of a scientist, as well as its relation to the real word and of the public domain, follows a very similar structure.

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