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Ecosystem services as a post-normal field of science

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1. Introduction

As the concept of ecosystem services (ES) matures, more attention is focused on how it is applied in practice, how best to integrate ES knowledge into environmental governance (Guerry et al., 2015; Keune et al., 2013; Russel et al., 2016), and the role of ES researchers and other actors at the science-policy interface (Crouzat et al., 2017; Jax et al., 2018). We contribute to this dialogue by analysing the potential for the concept of post-normal science to provide a guiding framework for ES research. Post-normal science is an approach to knowledge generation focused on situations characterised by high uncertainty, that are value-laden and where decisions are urgent. While post-normal science has been considered retrospectively to describe developments in the field of ES (Fish et al., 2016), thus far the applicability of post-normal science as a guiding framework for ES research has not been explicitly analysed. This paper addresses this gap in the following way. First, we introduce the concept of post-normal science, its descriptive and normative roles and how these may apply to ES research. We then briefly review the current use of a post-normal approach in ES research. Finally, we discuss benefits and challenges of post-normal ES assessment, and develop the idea of post-normal science as a potentially useful posture to guide ES researchers in this value-laden, mission orientated field (Keune et al., 2013; Schröter et al., 2014).

2. Post normal science and its relation to ecosystem services

Post-normal science was initially developed by Silvio Funtowicz and Jerome Ravetz in the late 1980s and early 1990s as a response to perceived failures of the 'normal' mode of science (Funtowicz and Ravetz, 1994a, 1993, 1991). Normal science is understood as an expert led, problem solving approach of structured hypothesis testing within an accepted analytical framework (Kuhn, 1962). The key differences between normal and post-normal science are summarised in the Table 1. According to post-normal science, such an approach to science is not flawed per se, but simply insufficient for informing real world decisions (Funtowicz and Ravetz, 1993). Three key reasons exist for this, firstly, decision contexts tend to be characterised by high, potentially irreducible levels of uncertainty, leading to incomplete and potentially contested understandings (Funtowicz and Ravetz, 1994a). This includes both technical uncertainty, inherent in the available data, and epistemic uncertainty or 'unknown unknowns' (Funtowicz and Strand, 2007). Secondly, decisions have as much to do with desired futures states as they do with the processing of scientific information (Jardins, 1997; Norgaard et al., 2009). Finally, real world decision making does not allow for repeatable rounds of hypothesis testing as typically practiced in the normal mode of science. In such situations, the possibility arises for multiple, but equally legitimate understandings of the problem situation, suggesting the need for an alternative mode of evidence gathering.

It is useful to understand post-normal science as playing both a descriptive and normative role (Strand, 2017). We will take both of these roles in turn, and discuss first if ES research attends to post-normal situations, and secondly how the normative prescriptions of post-normal science might be applied to ES research.

As discussed by Crouzat et al. (2017), some ES research belongs to the realm of pure science and is totally disconnected from decision contexts. Here, the situation may well be characterised by high levels of uncertainty, but the relative disinterest from stakeholders and absence of political time pressure leads to this research being conducted through the methods of normal science. This work may be linked to ecological functioning behind ES, but be approached as a purely scientific question, detached from any decision situation. Yet ES is by conception a mission-orientated field, and is mostly carried out with the intention of informing policy or guiding decisions (Jacobs et al., 2013). These situations are likely to exhibit high uncertainty, be value-laden, and require urgent decisions. Uncertainty, due to the complex socio-ecological systems through which ES are produced; with non-linear, stochastic relationships and complex feedback loops leading to unanticipated responses to management changes (Chan et al., 2012; Guerry et al., 2015; Sagoff, 2011; Waltner-Toews et al., 2003). Value-laden, because any question about the environment inevitably involves dimensions of how people feel they, and others, should live in the world, how people relate to the non-human world and the type of world people want to live in (Irvine et al., 2016; Jardins, 1997; Kenter, 2016a). And urgent, because environmental problems can arise unexpectedly and require swift

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Table 1
Summary of main attributes of normal and post-normal science. Adapted from Strand (2017).

Feature	Normal	Post-normal
Descriptive		
Urgency	Research question not linked to impending decision/ political choice	Research question linked to impending decision/political choice
Level of certainty	Situation is characterised by normal, statistically determinable levels of uncertainty	Situation is characterised by both technical and epistemic uncertainty leading to unpredictable system behaviour and the possibility of multiple legitimate perspectives
Conflict	Limited stakes held to the outcomes of the research and small chance of conflict	Substantial stakes are held within the study system, and substantial chance for conflict over values or knowledge claims is present
Normative		
Validation of knowledge	Through scientific peer review. Validity of knowledge is based on the views of other experts in the field	Undertaken by 'extended peer community' including experts from a range of disciplines as well as stakeholders and decision makers
Reductionism vs holism	Individual components of wider socio-ecological system are primarily studied in isolation	Complex systems approach, aiming to understand environmental, social, economic and political aspects of a situation (and interactions between these)
Knowledge types	Data generated through established scientific protocols	A plurality of different knowledge types is considered from diverse academic disciplines and local, indigenous and traditional knowledges

responses. Also, ES management is often incorporated into policy cycles with finite decision points and time frames (Kenter et al., 2014). Thus, the majority of ES research is likely to be conducted in 'post-normal' situations.

In response to such situations, post-normal science reconstructs knowledge generation as a co-productive process between scientists and stakeholders which is intentionally critical, deliberative and epistemologically pluralistic. This is achieved through the inclusion of 'extended facts' and scrutiny from an 'extended peer community'. Extended facts include multiple types of knowledge about a situation that can contribute towards a more holistic understanding of the complex socio-ecological system (Aslaksen et al., 2013; Bremer, 2014; Ravetz, 2011). This includes local and traditional knowledge, as well as the recognition of academic disciplines that may previously have been neglected as legitimate lines of evidence in environmental decision-making. Importantly, this pluralistic outlook regarding legitimate epistemologies does not equate to relativism, where all knowledge claims are considered equally valid. It is necessary to recognise that multiple, honest knowledge claims can co-exist, and establish a process to eliminate erroneous or dishonest claims to knowledge (Funtowicz and Ravetz, 1994b).

This validation is achieved in part through the creation of extended peer communities. These can take various forms, however a common feature is the inclusion of both experts and non-experts who use their respective knowledge and expertise to evaluate policy proposals, including their scientific and non-scientific evidence base (Dankel et al., 2012; Funtowicz and Strand, 2007; Hisschemöller et al., 2001). This shift in the knowledge generation is intended to serve the dual purpose of collating diffuse knowledge about a problem situation to improve the quality of decisions, as well as democratising decision making and avoiding the hegemony of any one worldview or normative position (Funtowicz and Ravetz, 1993).

Whilst post-normal science questions the capacity of normal science to usefully inform decision making in value-laden, uncertain contexts, it does not reject its ability to create knowledge regarding relatively simple phenomena (Spash, 2015). We therefore follow Kay et al. (1999) and Spash (2015) in suggesting that post-normal science can be seen to rest on a realist ontology akin to complex systems theory. That is, there is a reality 'out there' that behaves as clusters of semi-stable system states that maintain themselves through positive and negative feedback loops but are prone to reconfiguration under certain conditions (Berkes and Folke, 1998; Folke et al., 2016; Kay et al., 1999). This position is consistent with early work from Funtowicz and Ravetz, where they themselves develop the idea of emergent complex systems as the philosophical basis of post-normal science (Funtowicz and Ravetz, 1994b).

Building upon this ontological foundation, post-normal science allows for a plurality of epistemologies through the inclusion of extended facts. The legitimacy and relevance of any single epistemological position then becomes a matter of societal debate, necessitating the inclusion of an extended peer community. In accordance with this critical realist perspective, we consider that post-normal science has three broad, complimentary normative prescriptions: 1) the adoption of a complex systems perspective, 2) engagement with a plurality of epistemologies and 3) a quality assurance process based on extended peer review. We will briefly discuss, with the use of examples, how ES research may adopt each of these requirements.

2.1. Complex systems approach

Early conceptual frameworks of ecosystem service production, such as the cascade model (Haines-Young, 2011), have been criticised for oversimplifying the complex socio-ecological interactions that underpin ecosystem services (Costanza et al., 2017; La Notte et al., 2017). Whether this is a fair criticism of the cascade model is a matter for debate (Potschin and Haines-Young, 2011), however it is true that recent conceptual frameworks seek to more explicitly represent systems interactions (e.g. Costanza et al., 2017; Díaz et al., 2015). Indeed a complex systems perspectives might be said to be truer to the origins of the ecosystem services concept, given its foundations in the work of systems ecologists such as H.T.Odum (Dempsey and Robertson, 2012; Odum, 1971).

An understanding of ES as emerging from complex socio-ecological systems can be incorporated into ES assessments in various ways. For example Villegas-Palacio et al. (2016) suggest beginning an ES assessment by undertaking an analysis of the physical, biotic, economic, cultural and political systems in the study site. This type of scoping exercise matches recommendations from a recent paper on ES best practice from the EU OpenNESS project (Jax et al., 2018). Other approaches to integrating systems dynamics into ES assessments involve such tools as causal loop diagrams; graphical schematics composed of nodes, connections and feedbacks within a system. These can be left as graphical representations, or used as the basis for computational modelling (Kenter, 2016b; Lopes and Videira, 2015).

2.2. Epistemological pluralism

There is a dual logic to adopting a stance of epistemological pluralism. Firstly, ES researchers may seek to gain a better understanding of social and natural elements of the ES being studied by drawing upon a range of academic disciplines, or through incorporation of traditional, lay or local knowledge. For example, Daw et al. (2015), demonstrate how scientific fisheries data can be combined with local, place based knowledge on social and economic dynamics to build a shared understanding of the socio-ecological system underpinning the delivery of coastal ES. Within this additive logic, non-scientific knowledge is being used to illuminate parts of the socio-ecological system that are not visible in the available scientific data.

The second reason to acknowledge the existence of plural epistemologies is their role in creating situations of divergent understandings within contexts of high uncertainty. Disagreements in post-normal situations may not be due to misunderstanding or dishonesty, but the result of separate interpretations of a situation based on different epistemological or even normative stances. Indeed, many core arguments over the ES concept itself result from fundamentally different philosophies of knowledge (Barnaud and Antona, 2014; Schröter et al., 2014). Increasingly, the ES concept is viewed as amorphous enough to accommodate a wide range of knowledge perspectives (Braat, 2018). The IPBES (The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) framework, centred on 'nature's contributions to people', also seeks to accommodate diverse epistemologies (Díaz et al., 2018), although some argue that the IPBES terminology still harbours implicit epistemic biases (Kenter, 2018). Regardless of the degree of epistemic inclusiveness at a conceptual level, epistemological differences cannot be dismissed at the level of individual assessments, where it will often be the case that conflicting knowledge claims exist.

2.3. Extended peer review

Many ES studies include stakeholder contribution and participation at different stages of the process (Dick et al., 2018; Ruckelshaus et al., 2013). For example, in Liquete et al. (2016)'s valuation of nature-based solutions for water pollution control, early engagement with local stakeholders allowed them to co-design assessment criteria and indicators. Although composition of stakeholder groups and their exact role varies, early engagement with a wide range of actors is increasingly considered best practice in ES study design (Jacobs et al., 2015; Jax et al., 2018; Ruckelshaus et al., 2013). From a post-normal science perspective, it is important that stakeholder groups do not simply provide information to researchers. These groups must also have ownership of the process, including oversight of the contributions by scientists and awareness of assumptions and framings underpinning academic work.

From the perspective of post-normal science, it is the role of the extended peer community to counteract potential biases and unstated assumptions that may arise due to; (1) the part of the system that is being focused upon; (2) the perceived legitimacy of different knowledge types; and (3) implicit epistemological and ontological assumptions underpinning specific methodologies (Funtowicz and Strand, 2007; Hockley, 2014; Jasanoff, 1996; Kull et al., 2015). With reference to case studies globally, Kull et al. (2015) in particular demonstrate how the scale, definitions and assessment methods used in ES assessments can be highly political decisions.

The above three elements of post-normal science can be seen as mutually enforcing. Multiple perspectives may exist, and multiple knowledge types are required *because* of the uncertainty inherent in complex systems. Oversight from an extended peer community is needed *because* of the possibility of multiple legitimate perspectives and potential for powerful actors to enforce their world view. As we shall discuss below, it is the internal consistency of these individual elements that gives post-normal science its value as a general framework for developing specific methodologies in ES assessment.

3. Is the ecosystem services field currently post-normal?

Thus far, we have argued that post-normal science appears appropriate to the majority of ES research situations, and we have described key attributes of post-normal science and exemplified how they apply to the study of ES. However, it is unclear to what degree the ES field as a whole is characterised by these features. To answer this question, we present the findings of a focused literature review that aimed to assess how post-normal science is currently being used in the ES field.

3.1. Method

Scopus and Web of Science (WoS) were selected as databases for a literature search. An initial search for literature that explicitly referenced post-normal science and ES yielded few results (WoS = 9, Scopus = 4). (Search string: ("post-normal science" OR "post normal science") AND ("ecosystem service*")). This confirmed our initial expectations that explicit consideration of post-normal science is highly uncommon within the ES field.

To identify further work in the field of ES that draws from post-normal science, we then performed a search for ES literature that cited key foundational texts in the field of post-normal science. We assumed that referencing of one of these texts indicated that the authors were aware of the concept of post-normal science, and that this may have informed their approach to the study of ES. To identify source documents, we performed a search for publications by Funtowicz and Ravetz from the years 1990–1995 (deemed to be the years in which the concept of post-normal science was established). We selected any publication that advanced the concept of post-normal science, and had approximately 100 citations or more in either database. These publications were taken as being the most likely to be cited in reference to post-normal science in ES literature. These included four articles and two book chapters which have been cited collectively 2096 times on WoS and 2131 times on Scopus (Funtowicz and Ravetz, 1991, 1992, 1993, 1994a, 1994b, 1994c).

The papers that cited these articles were next filtered down using the search string: "ecosystem service*". This, together with the initial search results, yielded a total of 94 peer reviewed papers. The abstracts of these articles were then scanned, and they were selected for further consideration if they: 1) made a conceptual contribution to the design of ES assessment, and/ or 2) presented the results of an empirical study which utilised an ES framework. Where we were unsure, the full text was considered before a judgement was made. Borderline cases not included in the final review can be found in the supplementary material, with an explanation of why they were excluded.

A table was created to record: 1) if studies were conceptual and/ or contained a significant empirical component, 2) the context in which the study authors had discussed post-normal science, 3) and if this framing explicitly informed their study. It was deemed that the post-normality of the situation (descriptive element) was difficult to judge without further knowledge of the study sites (see Table 1 above). Instead we used simple descriptors to record the relationship of the study to the science-policy interface, these were: i) 'pure science' (no stated intention to influence decision making), ii) 'action orientated' (stated intention to influence decision making), iii) 'linked to policy' (formally linked to decision or policy process) or iv) 'embedded' (stakeholders and decision makers are actively engaged in the research process). The assumption was that any study which was not classified as pure science may potentially be a post-normal situation. In addition, the presence of normative attributes (epistemological pluralism, extended peer community, and complex systems approach) were also recorded for empirical studies. It is noted that these are ultimately subjective judgements based on our reading of these papers, and a short justification for each decision can be found along with a full version of our recording Table in Appendix I in the Online Supplementary Material.

3.2. Results

A total of 31 studies matched the inclusion criteria and were reviewed. Of these, 17 were largely conceptual and the other 14 contained detail of empirical assessments of ES. It is worth noting that these identified 31 studies referencing post-normal science compare to approximately 3000 papers published on ES in 2016 alone (McDonough et al., 2017). These 31 papers appeared in 19 different journals, most with one article, except for 'Ecological Economics' with eight, 'Ecosystem Services' with five and 'Regional Environmental Change' with two. The earliest paper found was from 2003 (Chiesura and De Groot, 2003). As shown in Fig. 1, since 2014 there has been an increase in interest in post-normal science in the field, however this could also be an artefact of there being more ES studies published overall in these years.

Although other studies appear to have been influenced by post-normal science, only two explicitly stated that they were taking a post-normal science perspective. The first was a 2011 study published in Ecological Economics which used a participatory modelling approach to study ES trade-offs in the context of Integrated Coastal Zone Management (ICZM) for the Seine estuary (Cordier et al., 2011). The second was a 2014 conceptual paper comparing instrumental and deliberative paradigms for the assessment of cultural ES, also published in Ecological Economics (Raymond et al., 2014). In other papers, it was common for post-normal science to be only briefly mentioned (or a post-normal science paper to be cited) in the discussion or conclusion section. As is shown in Fig. 2 below, this was often in relation to uncertainty, to dealing with multiple value types or as a general idea akin to increasing participation.

Of the empirical papers, none were considered to be 'pure science', eight were recorded as 'action orientated', one as 'policy linked', and five as 'embedded'. All papers categorised as embedded, exhibited at least two normative elements of post-normal science, with three of the five exhibiting all three elements (Fig. 3). All three of the studies that did not adopt any element of post-normal science were classified as action orientated.

4. Post-normal science as a scientific posture in ES research

Our review indicates that post-normal science is not a common framing in ES literature and research. Aspects of post-normal

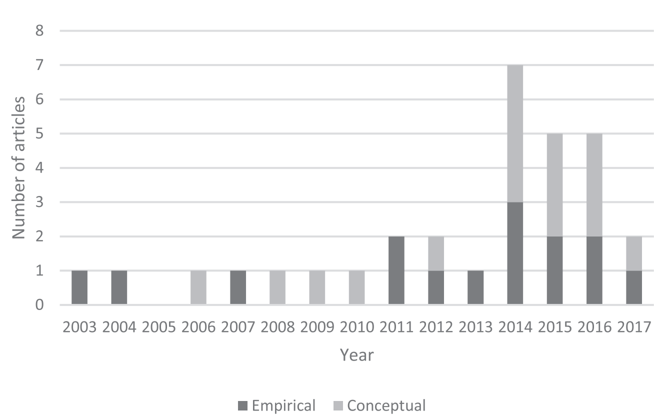

Fig. 1. Number of publications over time that met our search criteria. Showing both conceptual papers, and papers with a significant empirical component.

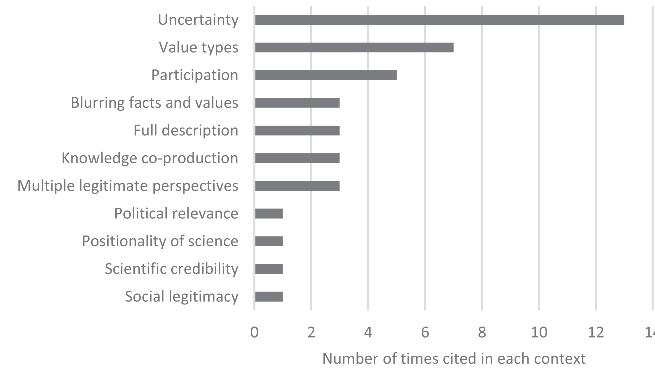

Fig. 2. Contexts where post-normal science was mentioned or one of the seed texts was cited in terms of publication count.

science did emerge however, and several studies were identified that, although not framed around post-normal science, could be described as such (Gilioli and Baumgärtner, 2007; Grima et al., 2017; Lopes and Videira, 2015). These studies tended to be more integrated in decision making or policy settings, supporting the applicability of post-normal science to ES assessments in decision making contexts. We acknowledge that our review is limited to studies with direct reference to foundational post-normal science literature, and we are therefore not able to comment on the extent to which elements of post-normal science appear in the ES field under different guises.

The reviewed papers reflect a number of threads that have received attention in recent ES publications; including questions around working with uncertainty, participation and knowledge validation, and value plurality (e.g. Carmen et al., 2018; Hamel and Bryant, 2017; Pascual et al., 2017). In this final section, we will discuss the potential contribution of post-normal science to these threads, and associated challenges of such an approach, before concluding on a way forward for post-normal science as a *posture* in the ES field.

4.1. Uncertainty

Discussion of uncertainty in ES assessment was the most common context in which post-normal science was mentioned. Attention to uncertainty within ES assessments is growing, with a recent paper outlining practical approaches to undertaking uncertainty analysis in ES modelling (Hamel and Bryant, 2017). Although this paper acknowledges the presence of qualitative uncertainty and 'recognised ignorance', it primarily provides guidance on best practice in using ES models, especially when dealing with a number of integrated biophysical and economic models. These approaches are useful for recognising and characterising technical uncertainty within ES assessments, yet need to be complemented by a recognition of epistemic uncertainty. Models have limited capacity to predict system behaviour that has not previously appeared, and may be entirely blind to aspects of the total system (Vatn, 2009). It is within this context of radical uncertainty, or indeterminacy, that some studies raised the potential of adopting insights from post-normal science (Heydinger, 2016; Navarro-Ortega et al., 2012; Ranger et al., 2016; Spangenberg et al., 2015).

Post-normal science aims to reduce epistemic uncertainty by illuminating larger parts of the whole socio-ecological system, therefore reducing the risk of completely unexpected outcomes from any subsequent intervention. Additionally, by defining system boundaries more explicitly, it may become clearer where residual epistemic uncertainty is likely to lie. This rationality for

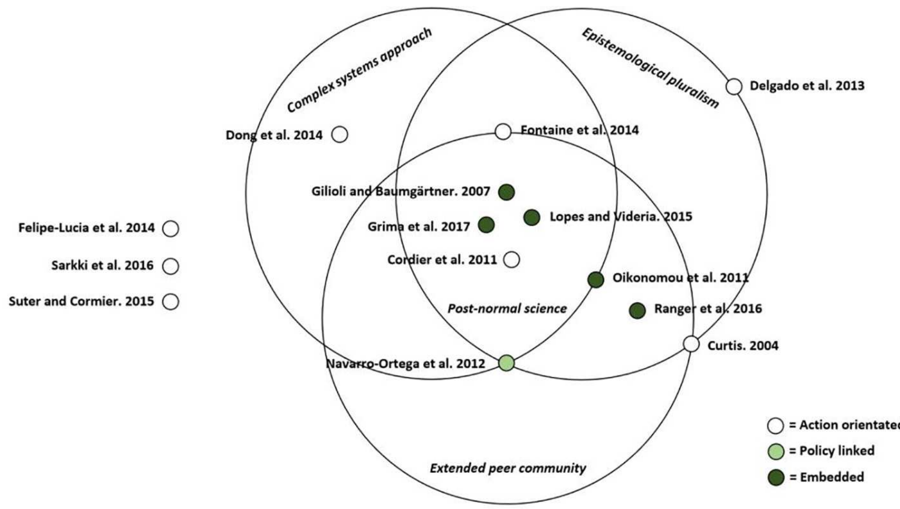

Fig. 3. Venn diagram showing the elements of post-normal science present in each empirical study. Studies are colour coded depending on their relation to the science-policy interface. Exact distances between studies on the diagram are arbitrary, their position was decided from a simple 'yes', 'no' or 'partial' classification for each of the three aspects.

including extended facts was prevalent in our review, see for example Oikonomou et al. (2011) or Navarro-Ortega et al. (2012).

How such forms of knowledge are conceptualised and integrated varied between studies. Spangenberg et al. (2015) states that stakeholders hold knowledge of social structures, such as institutions, cultural and religious rules, but there is no suggestion of the need to formally collect these data. This is in line with more recent work on integrated valuation that recommends developing an understanding of the socio-ecological context to inform study design, yet does not suggest the need to consider system dynamics per se (Mederly et al., 2016; Villegas-Palacio et al., 2016). Alternatively, other studies explicitly sought to understand system dynamics through the participatory creation of causal loop diagrams (Lopes and Videira, 2015).

One study attempted to integrate stakeholder knowledge of system dynamics into their computational modelling (Cordier et al., 2011). Yet such an approach has its drawbacks. As Funtowicz and Strand (2007) suggest, a trade-off exists in dealing with the two types of uncertainty. Where there is a focus on quantitative data with a high level of technical certainty, information relating to parts of the system that are less amenable to such levels of certainty, such as social dimensions, are omitted. Here, there is likely to remain higher levels of epistemic uncertainty and a greater likelihood that significant elements of the system are not accounted for. Conversely, including such information will invariably lower the level of technical certainty that is achievable. Indeed Cordier et al. (2011) suggest that adopting a holistic approach such as theirs can make it very challenging to accurately predict future states.

In sum, post-normal science seeks to reduce epistemic uncertainty in decision making through the inclusion of extended facts, going beyond the obviously quantifiable. Studies in our review attempted this in a number of ways, however a trade-off must be made when attempting to address both epistemic and technical uncertainty. This point is captured by Kull et al. (2015) in their example of a Madagascan study linking carbon offset payments to water quality benefits. They cite a study that achieves a high level of technical certainty for the small number of ES in question, but point out that this study is totally blind to other ES that may be impacted by the offset scheme being supported by its findings.

Much work in post-normal science approaches accurate predictions about the future with caution, and seeks instead to understand magnitude and direction of change at a broader system level (Kenter, 2016b). Whilst this may be appropriate for some situations, the management of many provisioning and regulating ES, such as fisheries and water quality, often requires a far higher level of technical certainty. Clearly such contextual considerations will play a role in the design of an ES assessment. The value of adopting a post-normal science posture is that it focuses attention towards the different types of uncertainty present in a research situation. This in turn informs the selection of knowledge types that it is necessary to engage with, and the trade-off that must be made between technical precision and whole system visibility.

4.2. Participation and knowledge validation

The participation of non-academics in research was another recurring theme across the papers reviewed. Nine of the empirical studies had some degree of stakeholder oversight in the research process, and five studies referenced post-normal science literature in the context of needing to increase stakeholder participation. Stakeholder input into basic elements of study design was the most common type of involvement in studies we reviewed. However, to be considered an extended peer community stakeholders must not be passive information providers, but must also act as arbiters of legitimate knowledge claims within the research process. A number of studies reviewed did seek to ensure that stakeholders had oversight of the generation of scientific evidence.

The need for such oversight is captured by De La Vega-Leinert et al. (2008) when they discuss the politicisation of models in policy, and expert guesses and value judgements that often guide the modelling process. Similarly, in the context of the planned German National Ecosystem Assessment, Albert et al. (2017) suggest that different actors should come together to define what is considered as reliable evidence. However, this becomes increasingly problematic as more complex techniques are adopted. The single empirical study in our review that explicitly took a post-normal approach lamented the issue of 'black boxing', caused by the translation of their participatory model into computational form (Cordier et al., 2011). Fontaine et al. (2014, p. 300) capture the issue well when they state: 'The challenge is thus to make this process-based calculation transparent enough for decision-makers without jeopardising the scientific precision of the simulator'. Even among relatively well informed stakeholders, it can take substantial time to reach the level of understanding needed to usefully comment on quantitative modelling approaches (Cordier et al., 2011), and stakeholders may not be willing to commit the time and motivation.

Ensuring oversight from an extended peer community requires careful consideration of how this will be done, and the time and training requirements that this may raise. Post-normal science does not necessarily intend complete, in-depth oversight of each step of the research process by the extended peer review community. Rather, adopting the posture of post-normal science creates a realisation that in complex systems, all knowledge is uncertain and the boundary between values and facts is fuzzy. This reflexive position makes issues such as politicisation and black boxing explicit, brings issues of oversight to the fore and ensures that knowledge claims, even those of expert scientists, are not taken for granted.

4.3. Value plurality

A third thread running through the identified papers is the existence of different types of values at play in ES assessments. Within reviewed studies, values were discussed as a source of uncertainty (Dong et al., 2014; Fontaine et al., 2014) that required a range of different approaches to generate an estimate of (Curtis, 2004; Ranger et al., 2016; Spangenberg et al., 2014). Although some studies saw a role for monetary valuation (Curtis, 2004; Suter and Cormier, 2015), many suggested that this was problematic on its own (Felipe-Lucia et al., 2014; Spangenberg and Settele, 2010; Suter and Cormier, 2015). Values were also considered as intimately entwined with participation, with the inclusivity and rigour of participation strongly influencing the degree to which value plurality is realised (Ranger et al., 2016). More broadly, it was recognised that institutional structures play a significant role in how values were expressed (Raymond et al., 2014; Sarkki et al., 2016; Spash and Vatn, 2006; Vatn, 2009).

Vatn (2009) identifies institutional arrangements geared towards social learning and communicative action as most suitable for ES due to the complex nature of the goods and services in question, and the potential incommensurability of value types involved. It is important that sufficient space is given to the consideration of the nature of the good as well as underlying transcendental values – the broad principles and life goals that people use to guide their valuation of particulars (Kenter et al., 2015; Raymond and Kenter, 2016) – through a rigorous process of deliberative value formation (Kenter et al., 2016; Raymond and Kenter, 2016). The contribution of post-normal science in this context is clear. A post-normal science process is specifically designed to allow for participant learning and the sharing and debating of different normative positions and value types. Indeed, much of the theoretical work on environmental values in relation to ES comes from the field of ecological economics, itself regularly identified as a post-normal science (Castro e Silva and Teixeira, 2011; Funtowicz and Ravetz, 1994a; Kenter et al., 2016,2015).

4.4. A post-normal science posture in ES research?

It is thus evident that aspects of post-normal science exist in ES literature under different guises. However, as we have seen, application of post-normal science to ES assessment generates both promises and challenges surrounding uncertainty, participation and knowledge integration, and value plurality. To resolve these tensions different degrees of 'post-normality' may be appropriate in different contexts. Issues arise due to the necessary trade-off between technical and epistemic uncertainty, the capacity of stakeholders to have oversight over highly technical scientific work and the difficultly of ensuring the right mix of stakeholders are effectively engaged in the process throughout. These issues require consideration in the precise design of an ES assessment, in light of the institutional and political setting in which it is being conducted.

For this reason, rather than prescribing a single and post-normal science approach, we advocate the promotion of a flexible but explicitly post-normal posture within policy and action-orientated ES research. To assist with this, we have developed a short list of questions that should be considered when approaching ES research in such a way (see Fig. 4). Importantly, the benefits of the post-normal approach are not derived from the application of individual aspects. The three identified elements of post-normal science are mutually enforcing, and together provide a coherent framework with broad applicability, a consistent philosophical underpinning, and in-built reflexivity. We conclude this paper with a discussion of these key benefits.

4.4.1. Broad applicability

The design and composition of an extended peer community and the nature of extended facts sought are not specified by post-normal science. What is specified is their purpose: to bring the best available information to bear on complex, normatively loaded questions in a deliberative democratic manner. The rationale of the broad elements of post-normal science is both normative, in that knowledge claims are linked to normative positions, and instrumental in that multiple perspectives can decrease epistemic uncertainty. Thus, post-normal science is specific and prescriptive enough to assist in ES study design, yet broad enough to be applicable in a wide range of cases.

4.4.2. Consistent philosophical underpinning

The need to consider with a wide range of knowledges is recognised in much ES literature (Carmen et al., 2018; Dick et al., 2018; Haines-Young, 2011; Mederly et al., 2016); yet to engage with knowledge claims in a consistent manner, it is necessary to start

Assessing the situation

- Are there high levels of uncertainty?
- Are there many stakeholders, and do they hold conflicting interests?
- Is this research likely to be used to inform policy or other particular decision-making process?

If *yes* to all of the above, then a post-normal approach might be appropriate:

Process oversight

- Which stakeholders should be included and when?
- What format will engagement with and participation of stakeholders take?
- What is the degree to which stakeholders have the capacity to understand and maintain oversight of different elements of the process?
- What training / capacity building is necessary to ensure stakeholders can meaningfully contribute and maintain oversight?
- Can the process be adjusted to enhance participation? What are the constraints (time, resources, other)?

Dealing with multiple knowledge claims

- What knowledge is pertinent to this context and how / with whom is it held?
- How will different knowledge claims be validated?
- How will different knowledge types be integrated?
- What differences in understanding might exist, and how will these be dealt with?
- What knowledge will be excluded (e.g. due to constraints in scope, time, resources, capacity)?
- What assumptions are made when answering these questions; how can they be made transparent to all involved?

Managing uncertainty

- What level of technical and epistemic uncertainty exist?
- How are these types of uncertainty addressed within the process?
- What trade-offs result from the chosen research design?
- How can uncertainty and trade-offs be made transparent to all involved?

Fig. 4. Suggested questions to consider when adopting a post-normal science posture to ES research. It is the intention that these induce reflexion, and are not a prescriptive list of how to conduct ES research.

from a clear philosophical position. In combining the realist ontology of complex systems theory with a social-constructivist account of epistemology, post-normal science offers a coherent framework for understanding multiple competing knowledge claims that neither collapses into relativism, nor requires arbitrary criteria of 'right' and 'wrong'.

4.4.3. In-built reflexivity

ES is an inherently mission-orientated field, and the work and actions of researchers have real world consequences at micro and macro scales. This reality means that ES researchers must be highly cognizant of their role at the science-policy interface (Crouzat et al., 2017). Acknowledgement of complexity and radical uncertainty, and the resulting blurring of facts and values, forces reflexion on one's own positionality within research contexts. Adopting such a reflexive position, and addressing assumptions and biases in the research process, is key to ensuring that ES is not the blinkering concept that some (e.g. Norgaard, 2010; Spangenberg and Settele, 2010) are concerned it has become.

In conclusion, we have clearly established that there is no widespread recognition of post-normal science within ES research, but aspects of post-normality can be identified that resonate with broader developments in ES research around managing uncertainty, participation and knowledge validation, and value plurality. The picture that emerges from our research is one in which post-normal science and ES can be co-informing and synergistic. By taking a more complete and explicit, but also flexible post-normal posture, future ES research can benefit from the philosophically consistent but broad and reflexive framework that post-normal science offers. At the same time, the inherent action-orientated nature of ES means that much ES research demonstrates post-normal science in action, and the post-normal science community could learn much from attempts to apply its principles in real-life situations in this field.

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Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoser.2018.03.021.

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