Exploring the socio-ecology of science: the case of coral reefs

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Abstract
In this paper I use data from interviews conducted with coral scientists to examine the socio-ecological dimensions of science, i.e. how science shapes and is shaped by the living world around it. I use two sets of ideas in particular: niche construction and socio-ecological value frameworks. Using these I offer socio-ecological criteria by which coral scientists evaluate the activities of coral science, more specifically which living systems are intended to benefit from coral science as an activity and the motivations behind this. The overall picture I present is one of coral science as activity primarily aimed at sustaining a diverse set of living systems, including humans, other organisms, species, and ecosystems, and the social practices associated with these. The value relations between scientists and aspects of these processes dictate how they respond to shifts in the socio-ecological context coral science is embedded in, explaining why the activities associated with coral science are changing as reef ecosystems are threatened. The implication is that natural sciences more generally are entangled with a greater number of social and ecological process than is typically considered, and that shifts in the activities undertaken by scientists may be driven by ecological as well as social and epistemic processes.

1. Introduction

> 'The whole of science is nothing more than a refinement of every day thinking.' – Albert Einstein (1936, p. 349)
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> 'Scientists try to eliminate their false theories, they try to let them die in their stead. The believer—whether animal or man—perishes with his false beliefs.' - Karl Popper (1968, p. 347)

Some accounts of scientific practice (including those in this volume) have begun to offer an ecological twist on existing descriptions of science as a social process (Aviles, 2023; Fangerau, 2022; Gupta et al., 2017; Lala et al., 2023; Rouse, 2014, 2023; Sanches de Oliveira et al., 2023, 2023; Thierry et al., 2023; Trappes and Leonelli, this volume). These authors marshal concepts from socio-ecological study to examine the nature of science itself, many of them applying the concept of the 'niche' and 'niche construction' to science itself. But are these to be thought of as literally ecological niches, or something more metaphorical? And is it theories, practices, scientists, or some other entity thought to occupy these niches?

In this paper I flesh out a socio-ecology of coral reef science, which is a science famously concerned with the survival of its study systems. I do this using data from interviews I conducted with coral scientists. 'For every coral scientist in the world' one interviewee claimed, 'the most pressing question is: will coral survive climate change?' Or, they continued, 'can we reverse the impacts of climate change quickly enough to save coral reefs?' (1002). Socio-ecology takes centre stage here, and science can be seen as explicitly aimed at more than just knowledge production. What does this tell us about the role of different forms of value in science?

Following Rouse (2014) and De Oliveira et al. (2023), I offer an account whereby scientists themselves are literally niche constructors who shape the living world around them. I connect this niche construction to frameworks for articulating how environments are valuable, drawing on ecology, environmental ethics, and economics, to help understand the goals underlying this constructive activity. Together, niche construction and socio-ecological value frameworks can be used to understand how activities within coral science are evaluated by coral scientists (as good or bad practice) and why the activities associated with coral science have undergone dramatic changes recently. This perspective may be relevant to many other areas of science too.

This analysis is supported by evidence from coral science literature, as well as more in-depth interviews I undertook with coral scientists. For a detailed explanation of the methodology, see ([Jones, 2023, p.29]), and for examples of similar work in philosophy of science, see Calvert & Fujimura (2011) or Veigl (2022). I conducted twenty-seven interviews, all in 2021, primarily with coral scientists working on macroscopic and ecological features of tropical coral reefs. Individual participants had often worked on reefs around the world, in various states of degradation, and all were very aware of the crises facing reefs generally. Most participants were based within the UK. As such, there may be unexplored national and institutional differences with other contexts[1].

Interviews lasted for around an hour, were semi-structured, and were designed to elicit information about how coral scientists conceive of and value their objects of study, and how this influences the concepts and practices of coral science. Interviews entailed a string of questions related to the reasons for working in their specific subject area, and their thoughts around the various ways reefs are valuable (such as in scientific, ecological, and economic senses). Interviews were conducted online, transcribed, and then qualitatively analysed. This analysis involved grouping sections of transcripts together into 'codes' or 'themes', where excerpts were all categorised as relevant to specific concepts of interest ('thematic analysis') (Riger & Sigurvinsdottir, 2016). These concepts were identified before the analysis took place but refined throughout the process (a kind of iterative analysis (Andow, 2016, p. 1130)). In this case, excerpts were grouped together due to their focus on the ecological factors shaping coral reef science, particularly the different kinds of entity intended to benefit from coral science, and on articulations of coral science activity which pertained to ecological functions, ecosystem services, intrinsic and instrumental value (I call these here 'socio-ecological value frameworks'). In this paper I use these excerpts and related concepts to build up a picture of the senses in which coral science is evaluated in terms of its impacts on the socio-ecological systems it is embedded in.

2. Science as socio-ecological activity

The activities of scientists have been studied in different ways. More traditionally they have been conceived of as part of a rational, progressive and self-correcting processes, whereby the prominence and success of particular theories and practices is tightly tied to how truth-conducive they are (for more on this, see Bloor (1991, p. 8)). More recently, explicitly social accounts of science

[1] I also draw on evidence from coral science literature, work by Irus Braverman (Braverman, 2018), and an international mailing list for coral scientists known as 'Coral-List', which all suggest that the broad conclusions of this paper are relevant to non-UK-contexts, however these sources are also anglophonic, and so leave further possibilities for differences with other linguistic and cultural contexts. There is not space to explore these differences further here. In terms of types of reefs, some participants had also worked on reefs in temperate, cold or deep water, as well as 'marginal reefs', that is, those found in unusual conditions such as turbid water. Some of these kinds of reefs are under less serious threats than non-marginal tropical reefs, but are still subject to efforts to study, understand and protect them from anthropogenic threats. In-depth analysis of differences between such areas of science is also not possible here.

have flourished, looking at things like how theories and evidence come to be accepted, how evidence is characterised, what forms of value drive these processes, as well as normative considerations about how science should operate to maximise things like objectivity, reliability, fairness or effectiveness (Bloor, 1991; Douglas, 2000; Goldman & O'Connor, 2021; Harding, 1995; Longino & Zalta, 2019)[2].

Here, I offer an ecological corollary to these epistemic and social analyses. There are two reasons to believe pursuing a socio-ecology of science may be fruitful. First, that strides in understanding have been made in other disciplines by synthesising social and ecological ideas. For example, in evolutionary biology through the eco-evo-devo synthesis, which has helped develop our understanding of interactions between living systems (Odling-Smee et al., 2003), or cultural evolution (Lala et al., 2023). Similarly, areas of ecology and marine science now increasingly include social as well as ecological considerations, with recognition that certain topics cannot be properly understood without both social and ecological factors included (I return to this 'social turn' at the end of the paper) (McKinley et al., 2020; Refulio-Coronado et al., 2021; Anderson et al., 2021; Bennett et al., 2017).

Second, these developments also offer an opportunity to build on previous attempts at using evolutionary and ecological theory to understand science (Bradie, 1986; Renzi, 2009), but with the benefit of the richer understanding of organism-environment interactions granted by modern ecology and evolution (as outlined in e.g. Kendal et al. (2011)). Accounts of science thus far have drawn on social, evolutionary and ecological theories, and given developments at the intersection of these fields, it may be fruitful to look in more detail at how an integrated socio-ecological picture of science can improve our understanding of science as an activity. Where this is particularly true is when looking at values in science, which thus far have not been strongly connected to existing literature on values in socio-ecological contexts.

2.1 Science, values, and socio-ecological value frameworks

2.1.1 Values in Science

What makes for a good theory, concept, or practice in science? One answer is that they instantiate *epistemic values*, that is, ideals, virtues, heuristics, or goals which are directly conducive to the production of knowledge, such as accuracy, internal consistency, simplicity[3], and generality (de Regt, 2020; Longino, 1994, 1996; 2008)). But *non-epistemic values*, those which go beyond knowledge production, such as ethical, aesthetic and pragmatic considerations, may also influence science, and arguments have been made both for their costs and their benefits (Vellend, 2019; Hicks, 2014; Elliott & McKaughan, 2014; [Jones, 2021]).

There is debate about what makes values epistemic or non-epistemic, which of these should take priority, and when these values can have a legitimate or illegitimate influence on science (Hicks, 2014). Many have challenged the distinction between epistemic and non-epistemic values, arguing that this distinction is heavily context-dependent (Rooney, 1992; Longino, 1996, 2008; Brown, 2013; ChoGlueck & Lloyd, 2023; Schneider, 2020). A helpful related distinction has been drawn between 'constitutive' values, which are directly related to the goals of science (e.g. producing knowledge),

[2] For more on the different 'waves' of science studies, see Collins & Evans (2002).
[3] Simplicity might seem to be aesthetic and therefore non-epistemic. The relationship between aesthetics and truth is a complex one. For more on simplicity and aesthetic values, see Baker (2022) and Ivanova (2017). Others have argued that simplicity may be politically charged and so not as obviously purely epistemic as might be supposed (Longino, 1996)

and ‘contextual’ values, which come from outside of a scientific community (e.g. personal, social and cultural values) (Longino, 1983).

The sheer diversity of forms of science necessitates context-specific accounts of what makes for good science (Dupré, 1993, Chapter 10). Evaluation of scientific practice depends on the commitments of specific groups of people engaged in collective activity, rather than abstract universal principles divorced from a specific context (Hicks, 2014). Good science might instantiate some of a set of virtues, such as sensitivity to a wide range of evidence, openness to criticism, plausibility of assumptions, and more (Dupré, 1993, Chapter 10), but these virtues will vary depending on the context, the communities involved, the goals they have in mind, and a variety of other factors (Longino, 2008). Different groups have different goals, and so different constitutive values for their scientific practices, requiring philosophers to pay attention to specific communities (Brown, 2013; Hicks, 2014; Longino, 1983).

Here, I explore how the coral science community evaluates its own practices according to the kinds of socio-ecological outcomes they are conducive to, alongside concerns about knowledge production. Science can often be seen to be aimed at meeting human needs, which may not be easily partitioned off as a non-epistemic or non-constitutive goal of science. The production of practical knowledge, and of socially useful outcomes, can be a constitutive part of science, and values which relate to the pursuit of human wellbeing are therefore to be considered legitimate sources of influence on scientific practice (Longino, 1996; Hicks, 2014, p. 3292). I show here that something like this is the case for coral science.

This set of research topics, about the nature of good science, and the role of values in science, can benefit from a socio-ecological approach, including social and human considerations alongside considerations of the other living systems we inhabit, cohabit with, and are inhabited by. Alongside the values already discussed, the value of specific socio-ecological arrangements associated with certain scientific practices can be considered too.

2.1.2 Socio-ecological value frameworks

By ‘socio-ecological value frameworks’, I refer to concepts from ecology, ethics and economics for articulating how aspects of the environment are valuable. I use these to examine how the value of aspects of the environment shapes scientific activity, using them to enrich niche construction accounts of science, giving a sense as to why certain activities are being performed and certain entities prioritised. I use four concepts in particular: intrinsic and instrumental value, and ecosystem functions and services. Each may be used to refer to different sets of entities and goals, with different justifications for doing so.

Traditional environmental ethics offers two influential concepts for understanding value: intrinsic and instrumental value. Intrinsic value, roughly speaking, describes the value something has regardless of its utility for other entities, or value which is non-substitutable, that is, value which cannot be replaced like-for-like with something else (Batavia & Nelson, 2017; O’Neill, 1992). There are a suite of related formulations of intrinsic value, and debates associated with these, which I do not get into here. For the purposes of analysing coral science, intrinsic value can be attached to any entity, and when it is, that entity is being prioritised as valuable in its own right, rather than as simply a means to providing some benefit to something else (in practice, as we will see, intrinsic and instrumental value are often difficult to separate (Kagan, 1998)).

Instrumental value, on the other hand, is the value something provides for some specific purpose (Justus et al., 2009; Maguire & Justus, 2008). So algae has nutritional value for the fish nibbling on it, i.e. a form of instrumental value. But so too do cases not involving consumption or destruction, such as the value of the beautiful colours of a kelp forest for a scuba diver (here intrinsic and instrumental value shade into one another, with beauty often being described using either term). Importantly, if something is primarily instrumentally valuable, it is more likely to be considered substitutable for something else: any algae of the right type will sustain a fish (Himes & Muraca, 2018, p. 4).

Ecosystem services describe ecological processes which contribute to human wellbeing (Daily, 2003; Schröter et al., 2014)[4]. They encompass a wide range of processes, including the cultural and recreational benefits of an ecosystem existing, provision of income, food and shelter by an ecosystem (for example reefs providing fish for eating, and protection from waves) (Costanza et al., 2014; Gould et al., 2020). Ecosystem functions, on the other hand, denote more general important features of an ecosystem, typically those to do with supporting the ecosystem itself or living entities interacting with it (Jax, 2005). They may support ecosystem services or directly benefit humans, but not necessarily, and may instead benefit specific organisms, support certain habitats, or refer very broadly to flows of matter and energy through ecosystems (Bellwood et al., 2019; Jax, 2005). With ecosystem functions, the beneficiary could be a wide range of living systems (humans, organisms, ecosystems themselves).

These frameworks offer points of connection between scientific practice and socio-ecological activity, scientific practices ultimately being a kind of organism-environment interaction. They can be used to understand how coral science can be evaluated in terms of its socio-ecological impact: the entities it aims to support (or not), and the reasons underlying this (in terms of the value of these entities and the goals they help meet). This offers insight into the evaluative norms of coral science, building on previous work on the interplay of pragmatic and epistemic values in science, and on the range of different aims which can be constitutive of an area of scientific practice (Longino, 1996, 2008).

2.2 Niche construction

Next, it is important to understand how I employ the niche construction framework here. A niche is, broadly speaking, the environment of a living system which is relevant to it in some sense; that is, those environmental features which are tolerated by it, conducive to its survival (or some other goal), or influence it through natural selection (Odling-Smee et al., 2003). This definition is broad because the niche concept takes on slightly different meanings depending on the context, such as whether it is used in a purely ecological or evolutionary sense (see Trappes (2021)). Niche construction frameworks emphasise that living entities (typically, organisms) produce and alter their environments, or those of others, and these modifications are relevant to the survival and evolution of the system in question (Odling-Smee et al., 2003). Here I use specific aspects of the niche construction framework and apply them to scientific activity.

First, I use what Trappes et al. call the '*focal entity*' (Trappes et al., 2022). The focal entity of a niche is the entity which is being impacted by the niche constructive activity. When a termite builds a mound, this impacts the survival of the termite itself, for example, by providing it shelter, and so the termite is the focal entity of this activity. Termites also sometimes cultivate a fungus in the mound. The fungus also benefits from the shelter, and so is also a focal entity here (Turner, 2002). There are often multiple entities impacted by a given activity. Focal entities are usually organisms, species, or populations, but may also be ecosystems and multispecies groups (I explicitly include these in the analysis I offer here) (Chiu & Gilbert, 2015; Turner, 2002).

[4] Services are sometimes described as serving non-human entities, such as the idea of *services to ecosystems*, or services to non-human organisms, but I leave that aside here (Comberti et al., 2015).

The next consideration is which entity is doing the construction. Whilst Trappes et al. use *focal entity* to refer to both the organism which performs the constructive activity and the organism which is impacted by it, I distinguish these here. *The constructor* need not always be the focal entity, but often will be. In the termite case, the termites are the constructors of the mound in which they live, whereas (for the sake of this example) the fungus simply benefits from it, as a focal entity but not a constructor. Lots of entities have impacts on the environments of others, ranging from trivial ones to essential contributions to survival (or some other goal) (Jones et al., 1997)[5]. Sometimes, as with coral reefs, these constructive influences can be reciprocal or form a web across many organisms.

Finally, niches are defined with respect to a *goal*. A standard definition treats niches as the conditions which support persistence of a focal entity. Evolution-oriented conceptions will focus on conditions affecting the fitness of the entity, or its ability to reproduce. Other perspectives focus on the development of an organism, or the ability of a species to establish itself somewhere. Niches may also refer to conditions under which an entity can flourish, i.e. reaching beyond mere survival to embody some of its greater potential. Human flourishing is easier to spot, but this applies to other living systems too, especially plastic and complex ones which can engage with the world in a variety of ways, and where such ways can be more or less successful[6] (Rouse, 2023). There are also cognitive niches, i.e. an environment where an organism can process information about the world, or sense and respond to some stimulus (Bertolotti & Magnani, 2017). Others have discussed epistemic niches, i.e. the environment in which some epistemic agent can know something (Sterelny, 2003, Chapter 2)[7].

Finally, there are a few further relevant concepts which I return to at the end of this paper: *fundamental* and *realised* niches, the conditions under which an entity can exist, and those under which it actually does exist, respectively; niche *construction, choice,* and *conformance*, i.e. directly modifying your environment, changing your relationship to your environment (e.g. by moving to a new one), or modifying your own phenotype in order to change your relationship to your environment (Aaby & Ramsey, 2022; Trappes et al., 2022); and *niche destruction*, the modification of an entity's environment in a way which negatively impacts its ability to persist, or some other goal (Dorninger et al., 2023).

There is sometimes scepticism about the utility of niche construction frameworks, both within ecology and when applied to other areas. For those sceptical, I hope it is enough to say that it is primarily socio-ecological construction which is important here, and so the picture I have articulated is also compatible with related frameworks, such as ecological engineering, which comes with less

[5] These are sometimes called ecosystem engineers (Jones et al., 1997).

[6] Niche construction theory - and extended versions of evolution more generally - open up space for the success or fitness of an organism to be evaluated according to a range of different criteria beyond simply number of offspring or amount of genetic material transmitted by broadening out the focus of biology to include multiple channels of inheritance (such as behavioural, epigenetic, environmental and cultural modes) (Jablonka & Lamb, 2006; Odling-Smee & Laland, 2011, pp. 223–224). This makes it easier to consider, for example, the lifespan of an organism, its ability to grow and transform, or the suffering and pleasure it endures, whilst still retaining a grounding in biological considerations. In Joseph Rouse's work, specific forms of plasticity, such as behavioural plasticity, may be more amenable to analysis in terms of flourishing, but even comparatively simple organisms can have their environments evaluated in terms beyond simply contribution to survival and death (Rouse, 2023).

[7] I do not explore cognitive and epistemic niches in detail here, see Sanches de Oliveira et al. (2023) and Trappes and Leonelli (this issue) for more on this in a scientific context. Related to this are conceptual and scientific niches, which may refer to the environment in which scientific concepts or practices are perpetuated, as kinds of cultural trait (Lala et al., 2023). For the sake of simplicity, I do not draw strong connections with these here: there is enough on our plate as it is.

evolutionary baggage (Jones et al., 1997; Pearce, 2011). It is important to note though that there are explicit evolutionary dimensions to socio-ecological processes (Rouse, 2023), including the ones I discuss here. The activities organisms engage in, and the modifications they make to their environment, are shared and inherited and so persist in many cases beyond simply influencing one organism within their own lifespan. Niche construction here allows for spelling out which living systems (organisms, ecosystems, species) are involved in shaping environments, which ones benefit from this, and also invites connections with socio-ecological value frameworks.

2.3 Science, niches, and values

The sense in which I apply niche construction frameworks to science here is a literal one, building on work by Rouse (Rouse, 2014, 2015, 2016, 2023). On this view, science *is* niche construction: it shapes the environment of various organisms, including humans, in ways which persist and may be passed on (Rouse, 2016). Scientists (or groups of scientists) may be both the focal entities and the constructors of the niche.

By building, maintaining, investing in, and working in scientific institutions (labs, field sites, etc.), humans construct environments which allow them to manipulate natural phenomena so as to make them more understandable (Rouse, 2015). Coral scientists, for example, use small artificial patches of reef to study how organisms settle on reefs. They also collect young coral and rear them in laboratory conditions. In both cases scientists, acting as constructors, shape their own environments (the labs and ecosystems they work in) and the environments of other organisms (those of the coral they study). Both coral scientists and coral are focal entities here. Coral are also often constructors, their large impacts on other organisms in the environment (e.g. by producing habitats for them, and study systems for scientists) being a reason they are highly valued.

Environmental modifications undertaken by scientists help facilitate a conceptual and embodied understanding of a given phenomenon, which in turn enables further prediction, control and understanding related to it[8]. These modifications enable perpetuation of certain patterns of living, including social practices, material environments, and arrangements of living systems (Rouse, 2015, pp. 207–208, 2023, Chapter 9). In the coral case, our understanding of the study systems and their survival are deeply intertwined, and tied to the ways in which we value reef environments.

Science allows for future-oriented niche construction, not only shaping immediate environments, but considering ways environments might otherwise be and ways to bring these possibilities into existence. There are both cognitive and ecological dimensions to this behaviour. Through the design, use and inheritance of sets of scientific equipment, practices, and theories, scientists produce concepts and environments which allow them to understand, intervene on and shape the world more effectively, perpetuating valuable socio-ecological systems in the process (Rouse, 2016).

Science, then, to paraphrase Einstein, is a refinement of everyday *activity*. The difference between scientific behaviour and behaviour of simple organisms is the use of concepts to articulate aspects of the world into manageable and manipulable chunks (Rouse, 2015). How scientists modify environments will depend on how aspects of the environment are valued. Here, socio-ecological value frameworks can help. If, for example, a threatened organism is instrumentally valuable to humans, it may be modified (e.g. selectively bred) to preserve this value. If an organism is actively disvalued, interventions may try to remove it. The ways in which aspects of reefs are valuable will impact how they are treated during scientific activity. Niche construction here connects science to

[8] The intertwining of the embodied and conceptual, and of understanding and intervention, being a common theme in biological sciences (Leonelli, 2009).

socio-ecology, by bringing considerations about the value of environmental features together with an analysis of the entities which are the focus of efforts to modify or preserve certain environments.

3. Which niches are relevant to coral science?

Using these frameworks, I now explore which entities' niches are being modified by coral scientists, and with what goals and forms of value in mind. To start, I look first at organisms, before moving on to species and ecosystems.

3.1 Coral scientists and science

In one sense, coral science helps perpetuate the existence and ways of life of coral scientists. Science, as a kind of paid work underwritten by a vast extra-scientific division of labour in the wider economy, enables the survival of its practitioners. In a basic sense, scientific activity provides scientists with food, shelter, and the other necessities of life, albeit indirectly. Here, scientists act as the focal entities of their own niche constructive activity. Clearly, this is not the main function of coral science, or even usually an explicit aim of it, and there are many more important and interesting features of coral science to consider. But these basic considerations do shape careers (and scientific activity), producing a kind of choreography of interests and opportunities that many people will no doubt be familiar with (Hangel & Schmidt-Pfister, 2017). This was a common theme in interviews:

> **Quote 1**
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> "Author: How did you end up studying coral reefs?
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> 1001: So I did do my undergrad in biosciences, but I always knew that I wanted to do marine biology. So for my Master's, I did a marine biology degree. … During that I got in contact with coral reefs, because we had a course and also an excursion to the Red Sea, and I just thought it was a fascinating ecosystem, very diverse, very complex. I also learned to dive while doing my Master's during a holiday in Thailand, so I thought it was a cool thing to do. So I asked the professor of the coral reef course if I could do my Master's thesis with him. And we found me a project and he offered me a PhD. …
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> Author: What led you to work more on the reef structure stuff that you're doing now? And [away] from the ecology stuff?
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> 1001: …Basically, where I got a job, because there's not so many jobs out there for us postdocs. And when I read the post, I thought it was really interesting." 1001
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> **Quote 2**
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> "Author: What made you want to study the reefs and the aspects of them you study?
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> 1025: I always liked the sea... I grew up in a city where there is a huge sea just close to my parents' house. And I used to go fishing and scuba diving. And it was always part of the culture, for my family and for my culture. So doing science was something new…
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> [discussing choice of which reefs to study]
>
> … Well, the reefs by themselves, it was kind of opportunistic, then, the beginning of my career, I entered into some projects where I was just trying to find an opportunity. … I had a professor that had a project to study the reefs along the entire coast. So I travelled across the entire coast studying so many different reefs. Then when I became a professor, I choose two of my preferred sites … I decided to concentrate some of my efforts there, not only because of scientific aspects, but because of personal aspects too." 1025

Quote 3

> "But I'm often diving on the reefs, or showing students coral ecology, and you see whales swim past and dolphins and whalesharks and turtles and things like that. So even though my research focus is on something very small, I actually get to enjoy and embrace and value everything else which is going on around, which is quite a powerful and empowering thing." 1015

Just as with most other professions, economic opportunity shapes activity, because the survival of the person doing the work is a consideration. But beyond personal and professional survival, coral scientists also construct a niche for themselves in terms of being able to engage in specific sets of practices which constitute a way of life they desire, such as taking part in activities which allow them to 'enjoy and embrace and value everything else' going on around them[9]. In this sense, coral scientists benefit from their work beyond simple payment for it. These activities are often valuable in themselves, beyond the value of the products they produce, or the value accruing to them through payment for their work. In Quote 1, the interviewee stresses that they always wanted to do marine biology, that they found coral reefs fascinating and enjoyed scuba diving, and that the project they most recently joined was a very interesting one[10]. In Quote 2, the speaker shows a similar pattern whereby their personal interests (diving, fishing) and childhood environment made a sea-oriented job desirable[11], and an interplay of scientific and personal aspects drove their later choice of study sites. So a key feature of coral science is that it provides an opportunity to engage in a set of practices which are valuable to the coral scientist, that is, it allows them to construct niches in which they can both survive and flourish[12,13].

The practices of coral science are also self-sustaining in a sense, allowing coral scientists to continue working as coral scientists. As with many other activities, coral science must be sustained by the relevant resources, particularly financial support. Scientific outputs such as articles are used to help drive acquisition of professional and personal resources, and to ensure future career success. These considerations have been articulated in studies looking at why scientists publish (Hangel & Schmidt-Pfister, 2017).

Groups matter here too. Scientific activities are bound up in the success of the organisations they are embedded in, for example lab groups and larger research institutes, again a commonly mentioned factor driving scientific publication (Hangel & Schmidt-Pfister, 2017). Here there is also self-oriented niche construction at the level of the laboratory, or groups of scientists, with research activity depending on grants. This research activity involves producing valuable scientific outputs, which may also be used to generate value elsewhere, such as economic value through translational research (Pinel, 2020). In this context, laboratories, and scientific activities more broadly, are sites of

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[9] Rouse calls this a 'practice-differentiated way of life' (Rouse, 2023, p. 18).

[10] Fun or personal satisfaction might be considered a non-epistemic value influencing science in this case.

[11] Many other participants said similar things: 'I've got an affinity for it [the ocean]' (1017); '[I liked] the idea of a creative career that I could choose my destiny with, but that would keep me in the ocean' (1002); 'I was always fascinated with things in the ocean' (1018).

[12] This has connections to the process of producing ecological baselines, something I explore elsewhere.

[13] There is an interesting interplay of recreational and professional marine activities here too, which I do not have space to go into here, but scuba diving and other marine activities formed a key part of narratives about deciding to go into marine science, and about enjoyable activities which form a part of their jobs. One participant articulated this explicitly: 'But I'm definitely not someone, and many of my colleagues are, who have a foundational fundamental drive to be underwater all the time … [I don't have the] "Jacques Cousteau thing".' 1026

production of value in various ways, including personal forms of value through credit and reputation, and economic value through licensing and selling of products, as well as through research grants (Pinel, 2020). These forms of value are often of the traditional instrumental sort, serving the purposes of some focal entity, in this case the coral scientist or larger institution they are embedded in, and acting as drivers of the niche constructive activity of scientists, as well as facilitating further niche construction in the future. The scientist here acts as caretaker of the scientific environment and the epistemic community associated with it, i.e. the groups of people involved in the maintenance of the scientific institution (Knorr-Cetina, 1999, p. 38; Meyer & Molyneux-Hodgson, 2010, p. 4). Here, the scientist or institution is the focal entity of the activity but also the constructor, and their activity is oriented towards a mixture of personal and institutional survival and recognition.

So scientific activity enables the continued existence of coral scientists, as humans engaged in a particular set of practices, many of which are valuable in themselves and which also produce valuable products: discovery, publishing, scuba diving, surveying, reading, attending conferences, lab work and meetings. Many of these practices are an important part of the lives of coral scientists, and the activities of coral science facilitate their perpetuation, as well as the perpetuation of the discipline and its institutions.

But coral science is not a purely self-oriented or utilitarian activity, driven only by the satisfaction derived from activities like diving or discovering things, or the aim of perpetuating coral science. Nor is it aimed purely at epistemic goals such as simply discovering more about coral. The value of many of the activities listed above depends on the relations coral scientists have with their environment and other living entities, the attitudes and experiences they have towards and with them, and the webs of mutual dependencies between parts of the systems in question. Care for other organisms, and their less anthropocentric forms of value, matters too.

3.2 Non-human organisms

The previous picture leaves much to be desired. There are other focal entities to consider. To start with, coral science often does not benefit coral scientists: some aspects of it are at best mundane and at worst deeply unpleasant. And yet, many choose to stay committed to the field for much of their lives. Irus Braverman, in her studies of coral scientists, documents both this unpleasantness and this commitment, noting mass grieving by coral scientists for bleached reef systems (Braverman, 2016, 2018)[14], but also a reluctance to retire "until we've done our utmost best to make sure that this nightmare doesn't end the way many scientists think it will" (Braverman, 2018, p. 67). Here is a first glimpse of non-instrumental value and non-human focal entities in coral science, which were also reflected throughout my own interviews:

> **Quote 4**
>
> "Having been driven from a very young age to work and be interested in protecting nature, I think it was perhaps slightly inevitable that at some point, I'd have my attention caught by reefs, because I think they are the pinnacle of that question, of that challenge" 1003

A constitutive goal of coral science is laid bare here: "protecting nature". The protection of non-human entities is a key part of what coral science does, it being "the pinnacle" of that challenge. The wellbeing of the researcher and the researched are intertwined: the speaker was motivated to follow their personal desires, and to get a job which allows these to be acted upon, but these desires are

[14] See also Gordon et al. (2019) and Conroy (2019) on grief in coral science.

specifically tied to caring for nature, i.e. to help construct and maintain environments for other organisms.

This attitude is common throughout coral science. Activity which does not support other organisms is liable to serious criticism from other coral scientists, and if it does not meet that constitutive goal, may be considered a kind of scam pretending to be coral science:

Quote 5

> “I've been to places where they've tried to grow corals, restore corals … and it's not working … And it's annoying actually, because it's a bit of a scam. They know it doesn't work but it does attract funding. So it helps the marine station go along and it … helps their profile and stuff as scientists. But the fact that it's not working, I think is diverting goodwill and cash, away from something that might work. We've got to be aware of that, I think. I'm not saying no coral reef restoration works, but this particular example wasn't working at all, and yet they kept doing it.” 1016

This quote traces the niches I have examined so far. The speaker describes restoration activities which can support coral scientists in terms of their livelihoods, practices, and careers, as well as supporting the institutions they are part of. But in this case it does not support the right non-human organisms. Here, the importance of the niches of other organisms is made clear. The stress in this quote is on the need for coral science to be realistically aimed at supporting coral and other organisms, not simply supporting coral scientists and marine stations. Research here is being evaluated not just according to its epistemic features, but its socio-ecological ones too. Coral science, on this conception, ought also to contribute to the survival and flourishing of a range of other focal entities. The aim of supporting specific organisms was made explicit by other participants:

Quote 6

> “…I got a bit tired of documenting demise on reefs. I wanted to try and look into how to save reefs, rather than just be a witness to the demise and destruction. So we started working on spawning corals and looking into ex-situ spawning techniques, improving the tools available to conservationists and reef restorationists” 1015

Unlike the sustenance of coral science and scientists, which is a somewhat implicit result of coral science activities, supporting non-human organisms is an explicit goal of coral scientists. Quote 6 spells this out: the speaker worked on helping corals reproduce and wanted to try to save reefs. Through such coral spawning techniques, coral scientists aim to support coral organisms, and to ensure that their existence is a healthy one. Already this shows that socio-ecological context is relevant to the goals of science: when coral organisms are threatened or harmed, action is taken to not only understand but also to try and remedy this, ‘rather than just be a witness to demise and destruction’. These actions may involve directly engaging in conservation and restoration, or less directly developing tools to allow others to do it better. Even those scientists who do not believe in restoration as an effective tool still do work which helps understand how corals will respond to changes in their environment, and this is often justified in terms of helping them survive into the future, for example, by providing evidence to support measures to protect coral environments (Morrison et al., 2020)[15].

[15] On the other extreme, ex-situ conservation - growing corals in aquaria - is also something being increasingly discussed and advocated. This may be for the sake of the coral itself, or for longer-term instrumental purposes such as replenishing populations (and benefits to humans) in the future, (Zoccola et al., 2020). This is especially

To summarise: caring for nature broadly, and reef organisms specifically, is a constitutive goal of coral science. Non-instrumental and non-anthropocentric value, beyond the value of these organisms for humans, is an important driver of niche constructive activity. As a kind of scientific activity, understanding these systems is also an important aim, but the two are not easily separable. These considerations are recognised by evaluation of coral science by coral scientists: in at least some contexts, good coral science is that which shapes environments in ways conducive to the survival of a certain set of non-human organisms.

It is no surprise then that welfare is a key consideration during experimentation and sampling. One participant explained that clownfish make good laboratory organisms because they "don't get freaked out by being in a fairly small tank, because that is their natural environment to be in a small space." (1002). Another participant argued that trawling for scientific samples can be very effective, and that as a result "sometimes… it is defensible to collect using a trawl … to find out what's there, and necessary to protect [it]" (1020).

Both cases show a concern for perpetuating acceptable living conditions for specific reef organisms, albeit in different contexts (clownfish in the lab, reef inhabitants in the sea). When discussing trawling for research specimens the speaker felt the need to spell out the justification for harming individual organisms by linking it to protecting other organisms and species. This directly recapitulates the kinds of concerns sometimes articulated by those working with animals used for experimentation in translational medical research contexts, where there is a dialectic between the intrinsic and instrumental value of the organism, and correlation between organism wellbeing and their epistemic value as good experimental systems (Davies et al., 2018; Friese, 2019; Haraway, 2009). Fish are useful for scientific reasons, in part because we want to understand how to protect them and their environments in the wild, and so are cared for but also may be harmed in laboratory and field work, in order to help protect them and other reef organisms elsewhere. Reef organisms provide instrumental value for both humans and other organisms, and also have their own value as living beings worthy of protection, and so are a key focus of the constructive activity of coral scientists.

But this picture is not a simple one: some organisms are subject to less attention within coral science, or actively negatively valued. Some ecological arrangements, such as those overrun by algae, bacteria, invasive lionfish or crown of thorns starfish (which eat coral), may be seen as degraded, and subject to attempts to change their composition (Haas et al., 2016; Rachmilovitz & Rinkevich, 2017)). Organisms may be considered undesirable and subject to practices focused on reducing their prevalence in a certain location:

> **Quote 7**
>
> "And so my thesis … was looking at how crown of thorns outbreak affected the reef communities. But then … I worked on how to best kill crown of thorns starfish, which ended up being a huge side project." 1007
>
> **Quote 8**
>
> "… I've also done work on invasive lionfish … Looking at how effective removing lionfish is ... So I did a lot of diving and spearing lionfish for my masters." 1011

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the case since anomalously high sea surface temperatures in Spring and Summer 2023 caused very high rates of mortality due to bleaching in various places, including restored reefs (Coral-List, 2023c, 2023b)). I return to this later.

Not all organisms are equal in the context of coral science. Some are seen as an undesirable presence on a given reef, as with crown of thorns starfish which alter reef systems when found in large numbers[16]. Lionfish are similarly seen as disruptors of reef ecosystems when they are in environments outside of a certain historical range (Diller et al., 2014). These disruptions are seen as bad for other organisms, humans included. Research and interventions may be undertaken to prevent and reverse such disruptions, as above with studying how to kill crown of thorns starfish, and lionfish. Here, epistemic practices are simultaneously ecological. The value of these organisms drives how they are classified and treated[17] and the constitutive aims of coral science involve consideration of the wellbeing of a wide range of organisms. Coral science is oriented in a way as to favour some organisms, and some arrangements of organisms, over others. Some parts of reef systems may be subject to modification in order to sustain others.

3.3 The human species

Coral science is also heavily focused on *groups* of organisms. The human species (or some constituent community of it) is a commonly invoked focal entity in the niche constructive practices of coral scientists, particularly via the concept of ecosystem services. Ecosystem services are typically defined as the 'ecological characteristics, functions or processes that directly or indirectly contribute to human wellbeing' (Costanza et al., 2017). Put simply, they are the processes in nature which people derive benefits from, i.e. processes which 'sustain and fulfil' human life (Daily, 2003, p. 227). Ecosystem services are invoked extensively in coral science. They are often used near the beginning of scientific articles to emphasise the importance of reefs, but may also appear elsewhere in the text:

> **Quote 9**
>
> "Author: … do you use the term ecosystem services in your work…?
>
> 1009: Usually in the first paragraph of the introduction
>
> Author: And why in the in the first paragraph?
>
> 1009: Well, the work that I'm doing, I guess it's not directly related with giving recommendations for policy or this kind of thing. … but when you're introducing your topic, if you're writing a paper, then obviously … your target audience is someone who doesn't know what a coral reef is ... So you tell them these are systems which are really important. They provide these key ecosystem services, or key functions." 1009

Ecosystem services are employed in a nuanced way by coral scientists, part of a delicate interplay between the importance of the various niches impacted by coral science. Scientists both actively embraced the dependence of humans on reefs, and criticised overly anthropocentric views of reefs:

> **Quote 10**
>
> "But arguably, what we should be focusing on is the value that they provide to these … 500 million people who rely directly on reefs … they need them to be storm barriers… to be able to harvest their fish … so I think we … can think differently about engineering reefs to survive" 1026
>
> **Quote 11**

[16] For more on the crown of thorns problem, the trickiness of deciding if such outbreaks are natural, and on the assumptions connected to such investigations, see Sapp (1999).
[17] For more on this in the context of invasive species, see Helmreich (2009, Chapter 4).

> “So, for example, the intrinsic value of biodiversity, the intrinsic value to humans, is not economic … it's measured in other things, and you can't put an economic value on it. So I think [ecosystem services] can be quite dangerous. And then also just the idea that it is a service to humans, does have some issues with it in that, … that's not what they're there for. You start to see it as a something that's... that whole issue of being put there to provide resources for humans, is not something that I think is true” 1010

In Quote 10, another goal of coral science is invoked: to protect the ways in which reefs are valuable to many humans who depend on them. Reefs undergird a variety of practices tied into the ways of life of many communities, via things like wave protection, provision of food, tourism income, intangible, aesthetic, recreational and cultural benefits (Moberg & Folke, 1999; Costanza et al., 2017). The various ways humans depend on and benefit from reefs is a key concern of coral scientists, and an important aim of coral science is maintaining reefs in a way which protects people (in common with other areas of science where human wellbeing can be a constitutive aim (Longino, 2008)). Here, the focal entity is the human species, or communities of humans, and scientists act as niche constructors, for reef organisms but also for human communities, by enabling reef organisms to continue to construct niches for these communities. Coral scientists are acutely aware of this web of interdependency.

As Quote 11 shows however, this aim – of maintaining human benefits from reefs - is not unequivocal. Ecosystem services can be problematic, particularly when used to reduce reefs to systems for providing humans resources. Ecosystem services can make the systems they are applied to substitutable, i.e. they can imply that replacing a reef with an equivalent system – in terms of specific features, such as fish production, recreational value, or ability to protect from waves – would involve no significant loss. Interview participants were often opposed to this way of thinking, particularly when taken to be exhaustive of the value of the reef. Reefs are seen as valuable in a much greater sense than simply for the tangible and substitutable things they provide humans. One participant articulated this at length:

> **Quote 12**
>
> “if we were to lose reefs tomorrow... I think we'd actually lose the beauty faster than we lost the [service] value, because I think the beauty would just be gone. And that would be a moment in history that we could never get back. … if we were to lose all the inhabitants of the reef, no matter what else cropped up in its place … you've burned the Mona Lisa, you can paint another painting if you want, but it's not going to be the Mona Lisa is it? It's going to be different. Whereas the difference with the [service] value is that it is feasible to think that actually, reefs might be replaced by something else that have equal value in terms of fishing output, or in terms of coastal defence … because from a purely like, pragmatic approach … there's papers out there, that show actually, a degraded reef, if you fish it in the right way, can have a similar fisheries output value [to] a healthy reef. … So I think, in that sense, the pragmatic value of reefs, probably, I sort of hesitate to say it because it sounds a bit like you being a bad guy, but I think it probably isn't irreplaceable, in the same way that the slightly less measurable beauty of a reef probably is irreplaceable.” 1003

The point here is that whilst supporting human wellbeing via instrumental means can be seen as *an* aim of coral science, it is tempered by other considerations, and that the value of coral reefs, value which shapes coral reef science, cannot be reduced to simply the value these systems provide to the human species. To do so potentially licenses the destruction of other valuable aspects of the reef. Constructing a niche at the level of the human species is one aim of coral science, but is one aim amongst many. The prevalence of ecosystem services in coral science might at first make it seem a very human-centric science, but the nuanced deployment of the ecosystem services within coral science reveals a much broader concern with both humans and a range of other non-human entities.

3.4 Ecosystems and non-human species

Criticisms of ecosystem services point to another aim of coral science: supporting non-human species, and ecosystems more broadly. These features are often subject to investigation, conservation, and restoration:

> **Quote 13**
>
> "And we're just talking about corals. There's a whole reef of things that rely on corals. That whole reef of things is going to go away too, if we can't get reefs in better shape. And I view this as the tip of the iceberg honestly" 1026
>
> **Quote 14**
>
> "With coral reefs, you've got … this type of branching coral allows for that type of fish, and that invertebrate to fit in. So all that complexity, allows for these species to find their niches within that habitat and that ecosystem, and then they can thrive and contribute to the function of the entire reef…
>
> If you lose coral reefs, you lose that complexity and that ability to contribute to that diversity. And so you would lose those species that rely on those coral reefs, maybe even also pelagic species [such as fish] that use coral reefs as their stepping ground before they move out into the wider ocean as well." 1004
>
> **Quote 15**
>
> "… and this ties into restoration a lot, that, I think it's now unrealistic that we're going to be restoring reefs to any kind of pre-industrial levels. And so it's more looking at preserving function, which would be things like having herbivores and predators and those trophic chains preserved and having some kind of coral that provides structural complexity for other species, and that kind of stuff. So preserving the functions of a pristine reef rather than the exact species and diversity of a pristine reef." 1007

Here there are appeals to some other important beneficiaries of coral science, and to some associated aims of scientific activity. In the first quote, the speaker appeals to the 'whole reef of things' that rely on corals. Corals are instrumentally valuable for the other organisms on the reef. In Quote 14, the speaker appeals specifically to certain types of organisms (coral, fish, invertebrates), as beneficiaries of a healthy and functioning ecosystem. They also refer to the diversity of the system, and to the ecosystem as a whole as a beneficiary. So beyond constructing niches for humans, coral scientists also have concerns for the existence (intrinsic value) of various focal entities: entire ecosystems, and the species and organisms which compose them, including also their instrumental value to one another as niche constructors.

One way this is emphasised is through the notion of ecosystem functions, mentioned in Quotes 14 and 15. Here, the aim is to understand and protect specific arrangements of organisms and abiotic components, as larger systems which operate in certain ways. Hence the speakers talk about the different roles in the system: corals as contributing to complexity; herbivory and predation; trophic chains (how energy flows through the system); habitat provision. Speakers refer to ensuring certain patterns of ecosystem arrangement continue, including by physically intervening to do so. Similar ecological processes have been named as the 'core functions' of coral reef ecosystems in scientific literature (Brandl et al., 2019).

Ecosystem functions are often described in very broad ways, for example as 'processes and the causal relations that give rise to them', 'the role of organisms within an ecological system', 'the overall processes that sustain an ecological system', and 'the services a system provides for humans or other organisms' (Jax, 2005). When raised in interviews, these processes were – in line with these definitions - typically to do with supporting non-human species, or else were related to the larger ecosystem:

> **Quote 16**
>
> "And then you've got the more kind of functional ecology side of coral reefs, which in the absence of all humans would still be there. ... One of the main features is the bioengineering of corals. They build habitat, reef forming corals create environments that then host exceptionally high levels of biodiversity. And provide both structurally stable, but also environmentally stable environments for animals to live in, and some plants." 1002
>
> **Quote 17**
>
> "In the way I think about it, a function is something to do with the sort of the inherent way the ecosystem is stitched together, and the way that the community of different animals and plants and organisms on the reef, work together to create a property of the ecosystem that wouldn't be there if it was just single animals. … an ecosystem function might be like herbivory, or bioerosion… calcification, the respiration/photosynthesis balance, that sort of thing." 1003

Again, these quotes show concern for a whole array of living entities and their patterns of interaction: for self-sustaining ecosystems beyond individual species or organisms, and for biodiversity, stability, bioerosion, herbivory and habitat formation. The International Coral Reef Society, the largest professional organisation for coral scientists, displays this concern for ecosystems in its mission statement: 'ICRS promotes the acquisition and dissemination of scientific knowledge to secure coral reefs for future generations' (International Coral Reef Society, 2023). The ICRS is not a conservation organisation but an academic body, and yet scientific knowledge here is explicitly put in service of perpetuating coral reef ecosystems. The standards of this community are thereby at once epistemic and socio-ecological, with 'pragmatic' values playing a constitutive role in scientific activity here.

This concludes the main bulk of the analysis of coral science that I offer here. No doubt other kinds of beneficiary could be picked out. The main point is that coral science is focused on the larger scale picture, the reef itself, as well as the human populations, non-human species, and individual organisms present. There are a whole set of intended beneficiaries of coral science here, and these will all be impacted by scientific activities simultaneously. Many of these entities are simultaneously niche constructors and focal entities. But where does this leave a socio-ecological account of coral science?

4. Putting it all together: the socio-ecology of coral science

To recap, niche construction is the activity undertaken by a living system whereby it shapes environments in a way conducive to certain goals: survival, development, fitness and reproduction, flourishing. Ecological value frameworks - instrumental and intrinsic value, ecosystem services and functions - can help flesh out the goals and entities involved in such activities.

Coral scientists undertake work which ultimately enables the transformation and maintenance of environments in a way conducive to the persistence and flourishing of the set of living systems considered to represent a desirable, healthy or functioning ecosystem, and which factors in the value of the environment for other lifeforms. They actively seek to aid the survival, development, and reproduction of specific reef organisms, the persistence of the overall ecosystem (and of dynamic ecosystem processes), and the flourishing and thriving of themselves and other organisms (or indeed the ecosystem itself), on top of perpetuating coral science as a process, and also of traditional scientific concerns such as producing understanding. This requires engaging in activity which simultaneously supports their own way of life, but also enables the persistence of the ecosystems and organisms they care for, and allows scientists to cognitively engage with the reef system[18]. Learning about reefs simply for the sake of knowing about them is still a constitutive goal of coral science, but blurs into efforts to help save the ecosystem, and both are tied to the flourishing of the coral scientist, and of the human species and the organisms and species associated with the reef. Coral scientists are caretakers not just for epistemic communities (Knorr-Cetina, 1999, p. 38; Meyer & Molyneux-Hodgson, 2010, p. 4) but also for broader multispecies communities, both in laboratory and field settings.

Coral science is, on this view, about perpetuating certain sets of organisms, species and ecosystems, and ways of life associated with them, such as appreciating, diving on, studying, being protected by, and eating from reefs. Interventions to remove or replace other entities, such as invasive or undesirable species, or organisms and ecosystems poorly adapted to projected future conditions, show how coral science is engaged in a kind of tussle between possible socio-ecologies[19]. There is tension between different sets of practices and associated socio-ecologies which connects directly to the socio-ecological tugs-of-war playing out around the world. The ways of life of the organisms on the reef (their life histories) are also bound up in these. Give that current human activity is incompatible with the continued existence of coral reefs in their current form, coral science finds itself the site of a negotiation between incompatible activities. Fossil fuel use, industrial fishing, pollution-generating endeavours, and various other practices all undermine the continued existence of reefs and coral science in their current form. Anthropogenic and other factors push ecosystems in one direction, e.g. towards reefs dominated by algae, or tropical arrangements in traditionally non-tropical areas, and coral scientists respond by categorising them in positive or negative terms, or studying ways to stabilise or dislodge them (Graham et al., 2013; Vergés et al., 2019).

4.1 Evaluating coral science

On this interpretation of the views of coral scientists, socio-ecological goals play a constitutive role in coral science. More specifically, coral science involves the (conceptually mediated) construction and maintenance of a set of niches associated with coral reefs, including humans and non-humans. Good

[18] The scientific activity I am discussing here includes both run-of-the-mill observations of organisms within the lab or on the reef as well as more interventionist interactions which perturb the environment. Moving through environments and observing them can be captured in the notion of niche choice, that is, an organism (coral scientist) modifying their relation to their environment (Trappes et al., 2022), in this case by moving into and observing it. Observation is a key part of coral science, and helps coral scientists understand the ecosystem, and to characterise it in terms related to the value of the entities present, for instance helping characterise the ecological makeup or state of health of the ecosystem, which is conceived of in terms of the presence, absence, abundance and relation of certain resident species and organisms at the expense of others. More direct interventions also involve manipulation of niches of the conformational or constructional type, i.e. by modifying the phenotypes of organisms or modifying their environments in order to enable them to persist, or to enable other living systems to persist.

[19] See Tsing (2015) for more on this, which she discusses using the concept of ‘latent commons’.

coral science responds to the threats these face in order to protect valued elements of this system. The 'system' includes both biological elements and the social practices they are involved with (Rouse, 2023). Good science, detectable by being conducive to the kind of virtues discussed under the label of 'epistemic values' – e.g. sensitivity to empirical fact, coherence with other knowledge, predictive power, intelligibility (de Regt, 2020; Dupré, 1993; Potochnik, 2017; Longino, 1983, 1996) - is also detectable in a socio-ecological sense by being conducive to the kinds of virtues associated with healthy or desirable living systems[20]. These socio-ecological virtues are of course only one part of the much broader set of the criteria for evaluating science, and may come into conflict with other virtues.

This is an extension of existing arguments about evaluating science. Dupre (1993) argues that the best way to evaluate the quality of the heterogenous activities of science is through their contribution to flourishing: 'Science is a human product … like other human products, the only way it can ultimately be evaluated is in terms of whether it contributes to the thriving of the sentient beings in this universe' (Dupré, 1993, p. 264). Longino (1996, 2008) has argued similarly that the capacity of science to positively impact human lives, particularly those of the most disadvantaged, can and should be seen as an important goal of scientific practice. Here science is a practice which is deeply wedded to our need to navigate, manipulate, and understand the universe.

I offer here a multispecies twist on this. Practices which focus overly on one element of the multi-entity reef system are liable to criticism by coral scientists[21]. Coral science is a product of the interaction of many kinds of living system, and can be evaluated in terms of its contribution to the flourishing or thriving of these: human and non-human, sentient and non-sentient. Society in general is sustained by interactions of humans and other organisms, species, and ecosystems, which prop open our ecological niches (Rouse, 2023, Chapter 9). Even the most anthropocentric activities must be concerned with other species then, if only for instrumental reasons. Areas of science seemingly well-insulated from the study of other living systems may therefore also, under the right circumstances, end up focusing on the survival of these systems.

4.2 Socio-ecological values in science

On top of traditionally invoked epistemic and non-epistemic values, here is a case of value relations between different living systems shaping scientific practice. The intrinsic and instrumental value of different organisms, species and ecosystems, and the functions and services connecting these entities, directly influence scientific activity. Science here is aimed at producing valuable socio-ecological outcomes.

The discovery of truth, production of knowledge, and contribution to understanding the universe are still important parts of the self-professed aims of scientists (Hangel & Schmidt-Pfister, 2017). But they are intertwined with personal, social, and non-epistemic concerns, as has been recognised in other cases (Longino, 1983; Hicks, 2014; Hangel & Schmidt-Pfister, 2017; Potochnik, 2015). Sociologists of science Latour and Woolgar show, for instance, that policy, evidence, and careers - i.e. public, epistemic, and personal factors – are deeply interconnected as drivers of scientific activity (Latour & Woolgar, 1986, p. 192). Science is also a personal process, a part of the niche of the scientist

[20] Just like the virtues of good science, virtues of healthy living systems (such as ecosystems) are a matter of debate and contention sometimes (Hobbs, 2016).

[21] The question of how to grapple with these multi-entity problems is a tricky one, and recapitulates some of core the problems of environmental ethics, namely which kind of entities are worthy of moral consideration (humans, living creatures, thinking/feeling creatures, ecosystems (Muraca, 2011)) but also involves other kinds of question too, such as the historical range of an organism, its impacts on other living systems, compatibility with expected future environments, and many other economic, political and biological issues.

themselves, as an entity interested in the discovery of new things about the universe. Curiosity – discovering truth for its own sake – is related to the flourishing of coral scientists and to the social practices they engage in.

Truth is an important part of sustaining the heterogeneous entities and ways of life associated with coral science, allowing scientists to better construct and maintain niches, but it may not always have a primary role. The goal of discovering truths for their own sake may take a back seat when the survival of some part of the multispecies nexus involved in coral science is at stake, just as truth may take a back seat when producing epistemic goods such as understanding or intelligibility. Scientific models and theories may idealise aspects of nature in order to meet epistemic and social aims (Potochnik, 2015, 2017). So too may they idealise aspects of nature to help perpetuate certain socio-ecological conditions, such as contributing to the flourishing of various types of living system. Ecological baselines, an important area of contention in coral science, are the quintessential example of this socio-ecologically-oriented idealisation (Jones, 2021). The interplay of science and wellbeing make for deep connections between ethics and epistemology here, and offer situated examples of non-epistemic values being constitutive of scientific practice (Hicks, 2014; Longino, 1996).

5. Ecologically-driven repertoire shifts

A socio-ecological perspective also augments our understanding of factors shaping scientific practice. On the 'repertoires' framework for understanding science, different areas of science involve particular sets of skills, practices, concepts, and other 'material, social, and epistemic components' (Ankeny & Leonelli, 2016). Often it is argued that these components of a given science depend on factors such as technological developments, and the age or 'stage of development' of the science (Collins et al., 2023). Here, I show that socio-ecological factors matter too: when the ecology of the study system starts to be threatened, break down, or radically shift, the activities engaged in by scientists will change too. This offers another set of drivers to explore for understanding what shapes science. The need to transform coral science to respond to socio-ecological changes was articulated earlier in the discussion about 'documenting demise' (in Quote 6), and discussed in similar terms by others:

> **Quote 18**
>
> "I think that as ecologists we get trapped in the 'documenting the decline trap' … I don't know if finding another unique way that reefs are impacted by climate change is going to change anyone's minds …
>
> I don't think that it's for lack of information, and if we just find one more fish who behaves differently because of climate change … that'll be the straw that breaks the camel's back, and all of a sudden we stop emitting carbon. So I think that there's a lot of interesting questions that we can explore out of general curiosity of understanding our systems and understanding how they will look in the future, but I think the most pressing question above all else should be a solution to the climate emergency." 1007

What matters here are pressing questions about how these systems will survive in the future, not simply epistemic concerns for how they operate. Contributing to a greater understanding of these systems in a way divorced from the struggle to keep them in existence may even be seen as bad, or a waste of time. The speaker labels this 'documenting the decline', a pejorative term for a kind of transfixion on doing largely epiphenomenal science whilst the object of study slips out of existence. This was articulated at length by one interviewee:

> **Quote 19**

> “academia still has the same set of incentives that it's had forever … publish papers, get grants, publish or perish, you know, this kind of thing. … And so those are the levers that push you in academia, where we have these giant problems over here, where those levers don't matter. And so then how as a young person am I supposed to get satisfaction about being in academia and doing this treadmill publish or perish thing, when what I really want to help with are these big questions ... I get that every time I give a talk now, and I don't have an answer ...
>
> And I had an opportunity to really pull back and think openly about science in a way that I hadn't in a while. And I really came to terms with, what's happening to coral reefs. And I had a crisis of confidence about the value of science, the value of basic research. … And so I really was thinking, what am I doing? … who cares about basic research, when you're not even going to have a research animal left in 25 years? What is the point? And it was very hard for me, because, here I have a lab full of graduate students who I've sold a bill of goods to, you know, basic research is good, incremental building bricks in the wall, this is all good, we're moving science forward. And suddenly, I really wondered if it was valuable. … I've softened my approach to that. But I still believe that science is not serving... basic academic research is not serving corals as well as it could and should. And part of it is my age, right? I'm older, I'm sort of beyond the peak of my career. So I'm seeing the whole arc of things. And the way in which academia is done is this slow incremental approach where you publish things.” 1026

Here, we see that more epistemic or self-oriented actions, such as curiosity-driven research and publication, can take a back seat when the systems being studied are under threat. The current incompatibilities between human and coral niches raises serious questions for the niche constructive activities of coral scientists: if something has to change, is it the reef ecosystem (or some component), us, or our relationship to it?

The niche perspective spells out the options clearly: we can try to engineer coral organisms to be compatible with impacts of our behaviour (e.g. higher temperatures), bringing their fundamental niches into line with our realised ones[22]. We can try, through geoengineering, to modify the realised niches of corals, to make our lives compatible with theirs once more (risking modifying environments of other organisms in the process). Or we can modify our own behaviour (and so our realised niches) to make it compatible with the existence of reefs. These options are not necessarily incompatible with one another, and are all being pursued in various forms. This is something invoked in arguments about using modifications to coral biology to provide time for human behaviour to change.

The way we value aspects of reef systems, e.g. intrinsically and instrumentally, will shape how we pursue these options. Are reefs a part of our environment to be modified, or something we should make changes elsewhere to save? A discussion on Coral-List (a mailing list for coral scientists) in April 2023 showed exactly these considerations, arguing that coral scientists should focus on *water restoration* (modifying the environment of the coral) rather than *coral restoration* (which treats them as primarily part of our environment) (Coral-List, 2023a).

The frustration articulated in the previous quotes is that coral scientists are unable to easily shift their behaviour to focus as strongly as they would like on simply helping reefs survive, be that through modifying the ecosystem itself or by preventing its environment from changing. The

[22] To recap: the fundamental niche of an entity is the conditions under which it can possibly exist. The realised niche is the conditions under which it does in fact exist.

incentive structure of academia poses barriers to this by forcing them to also concentrate on their own niches (i.e. their ability to continue existing, both as an individual and as a scientist) and those of other entities such as the organisation they find themselves in, through things like the pressure to regularly publish articles. There is also frustration at being unable to make changes at the scale of global CO_2 emissions, which is the most pressing threat to the socio-ecology of coral reefs and reef science.

This helps make sense of repertoire shifts in coral science and elsewhere. Reefs were considered stable ecosystems in the decades before mass bleaching and die-offs became common (Sapp, 1999). Once the ecology of coral reefs (and coral science) was noticeably disrupted, some scientists adopted repertoires from an area of science which is explicitly aimed at global scale management of socio-ecology: epidemiology (Ankeny & Leonelli, 2019). They borrowed concepts, tools, language and practices from medicine, for example a strong focus on using -omic sequencing technologies, on phrasing changes to reefs in terms of health and disease, an interest in intervening on the coral microbiome, and the development of large-scale epidemic-style international co-ordination (Ankeny & Leonelli, 2019)[23].

But this is just one set of repertoire shifts that can be expected for an area of science with a collapsing ecological base. Further repertoire shifts are visible: many coral scientists now engage with more radical or interventions practices, including conservation and restoration (Anthony et al., 2017; Braverman, 2018). Public outreach, science communication, and education are seen as important tools for helping protect reefs. In an interview conducted by Irus Braverman, one coral scientist articulated this explicitly: 'And that's not to say that we don't do good science, but we must communicate it to everyone … So it's about getting outside our comfort zone and communicating our science effectively so that people understand the problems.' (Braverman, 2018, p. 67). Coral scientists have used creative techniques to do this: giving public talks peppered with snippets of entrancing audio recordings of reef organisms to help motivate non-scientists to care for them, and developing online apps to get people engaged as citizen scientists in assessing reef health (Google Arts and Culture, 2023; Simpson, 2019). Others have taken part in documentaries like *Chasing Coral* to inform and inspire people to help address threats to reefs (Braverman, 2018, p. 257).

Many coral scientists have also diversified their repertoires to include engagement with policymakers, as a response to the failure of traditional scientific activities to meet the constitutive aims of coral science: the perpetuation of the socio-ecological system scientists have devoted themselves to studying. As one coral scientist describes in the book *Coral Whisperers*: 'I evolved into a much different scientist. I spend most of my time liaising [with] politicians, working with NGOs, going global'. This is a direct response to shifts in the socio-ecology of reefs (Braverman, 2018, p. 57).

The 'social science turn' in marine sciences and ecology also represents a socio-ecologically driven repertoire shift, showing a growing awareness of the need to understand human behaviour in order to perpetuate various living systems (McKinley et al., 2020; Anderson et al., 2021; Bennett et al., 2017). In other areas of academic research, shifts towards more radical activities, such as research moratoriums designed to force governments to act on existing evidence about the threat of climate change, or joining explicitly political protest movements[24], show a similar socio-ecologically-driven

[23] It is worth noting here that disease outbreaks on coral reefs are also a significant threat, contributing to the rise in a medicalised perspective of reefs.

[24] See for example the case of a climate scientist who chained himself to a J. P. Morgan building in Los Angeles in a protest against fossil fuel funding, as a part of the 'Scientist Rebellion' global movement of climate-activist scientists (Freedman, 2022).

repertoire shift, and a concern with the need to perpetuate the ecosystems which undergird the conditions of existence of academia and wider society (Glavovic et al., 2021; Thierry et al., 2023). Increased interest in the socio-ecology of science, as shown in this special issue and elsewhere, might be seen in this light too.

Finally, some scientists are also pursuing modification of coral biology to suit changing environmental conditions (Oppen et al., 2015), or development of indoor refugia tanks for coral (Coral-List, 2023c, 2023b; Muka, 2023; Zoccola et al., 2020). These represent a radical departure from the traditional activities of coral science, something to be expected if it is seen as multi-entity niche-constructive activity. Such repertoire shifts depend in part on personal expectations people have around the political and economic conditions of the future. If the kind of economic system we currently find ourselves in is to continue to exist – if, as is often said, it is easier to imagine the end of the world than the end of capitalism[25] – then scientists will be moved to construct niches which fit within a future capitalist socio-ecology, e.g. by heavily altering the biology of corals to make their fundamental niches fit with our realised ones, or by moving them indoors so their environment can be better controlled. If the outlook is less gloomy, smaller (or no) biological modifications may be deemed appropriate. The appropriateness of coral science activities depends on the current and future socio-ecological context that scientists and reefs find themselves in. In times of ecological stability (of the right kind), scientists mainly worry about perpetuating the social practices of coral reef science. Once the ecology underlying their scientific practices is threatened, it becomes imperative to protect and salvage that environment. As the process of undermining our ability to exist in the world alongside various other living systems accelerates, other areas of science seemingly insulated from environmental concerns may increasingly also focus on perpetuating socio-ecological conditions under which we can exist.

6. Conclusion

The view I have articulated here treats science as, in the words of Rosalind Franklin, something that cannot and should not be separated from everyday life (Maddox, 2003, p. 60). Coral science is a particular kind of socio-ecological system: a web of interdependent entities, which can be studied, protected and modified in order to help maintain the whole system, including the practices of coral science, the laboratories themselves, networks of scientists and reef organisms, and larger institutes and ecosystems they are embedded in. Coral scientists have the job of maintaining much of this web in the face of changing ecological conditions and largely static (but unsustainable) economic ones. Scientists here act as caretakers of epistemic and ecological communities, maintaining the whole socio-ecological structure associated with their scientific practices. Coral are important and charismatic niche constructors in this system, and so are key focal entities of coral science insofar as they then support the activities of a range of living things. When corals are endangered, coral science is too, as are the livelihoods of humans and other organisms tied into the flourishing of the overall system.

On this view, there are an underappreciated set of values which drive and shape coral science. Scientists have strong motivations to maintain certain ecological arrangements and entities within them. Science here is both about obtaining knowledge but also perpetuating desirable socio-ecological conditions. More purely epistemic activity takes a front seat only when these living systems are not under serious threat. Context can make seemingly pragmatic concerns trump epistemic ones (Hicks, 2014; Longino, 2008), and where reefs are valued differently, different aspects of the reef may be prioritised in scientific activity. When features of this system are threatened, the

[25] This is attributed to Slavoj Zizek and Frederic Jameson (Fisher, 2009)

scientific process may shift to direct attention and effort at protecting the relevant entities (this is not done by an invisible hand or some inherent self-correcting process, but often by conscious decisions and hard work). At the extreme, when the livelihoods of scientists or their study systems are threatened, or the social practices and environments of science disrupted, scientific activity can no longer continue, or continues in a much-reduced fashion[26]. Climate change threatens to do this to society in general, if it continues unabated long enough (Thierry et al., 2023), and so many other areas of scientific activity may end up focusing on how to sustain certain socio-ecological systems. Scientific activity, especially of the ground-breaking and exploratory kind, requires these certain socio-ecological conditions in order to take place, and if these do not exist, it may cease entirely.

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Informed consent: All interview participants were provided with information about the study before interviews took place, given an opportunity to ask any questions about the project, and gave their consent to take part in the study.

Data availability statement: The interview data used here is not currently available open access.

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[26] This builds on Rouse's argument that science is a hard-won set of activities which are not guaranteed to exist, but which depend on the existence of a set of environments and social practices in order to continue operating (Rouse, 2014, pp. 289–290).

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