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# Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability

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ABSTRACT

Ecosystem services (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to sustainable human wellbeing. The ecosystems that provide the services are 'natural capital' (NC) using the general definition of capital as a stock that yields a flow of services over time. But these concepts must be embedded in a whole systems view of the interdependencies between humans and the rest of nature, as espoused by ecological economics from its inception. Valuing NC and ES is therefore about assessing their contributions (in complex interaction with built, human, and social capital) toward the goal of sustainable wellbeing *of the whole system* of humans and the rest of nature. This recognizes that sustainable human wellbeing cannot be achieved without the wellbeing of the rest of nature. To achieve this, an integrated approach to valuation toward the three sub-goals of efficient allocation (E-value), fair distribution (F-value) and sustainable scale (S-value) is necessary. This article reviews these ideas, and discusses an agenda to improve understanding and valuation of NC and ES toward the goals of efficiency, fairness, and sustainability in a dynamic, whole systems context.

## 1. Introduction

Natural Capital (NC) and ecosystem services (ES) are obviously important in sustaining human life on earth (Costanza et al., 1997, 2017; Daily, 1997; Díaz et al., 2015; Millennium Ecosystem Assessment, 2005). The big questions include: how important? Over what temporal and spatial scales? What are the limits of humanity's ability to substitute for them? At what levels of stress do they flip to some other (less desirable) state? All of these questions require the ability to understand and model the interconnected, coevolving system of humans and the rest of nature (Costanza et al., 1993, 2014a). In addition, the answers to these questions are not purely academic. We humans have to make choices and trade-offs concerning ecosystem services, and this implies and requires "valuation," because any choice between competing alternatives implies that the one chosen was more highly "valued." That the alternatives are "competing" is important, because if we can find a "win–win" solution then no real choice is required, and we can avoid valuation. But most environmental decisions involve the problem of having to weigh and aggregate the myriad different kinds of "benefits" of a proposed action against its "costs." In most cases, these benefits and costs are both poorly understood and poorly quantified, especially in the long term. In addition, the future vision and social goals that define the degree to which something is a benefit or a cost are themselves evolving and changing. In doing valuation of NC and ES, we need to consider a broader set of goals that include ecological sustainability and social fairness, along with the traditional economic goal of efficiency. In this article, I'll first define value systems, value, and valuation as they relate to this broader set of goals. I'll then describe a broader approach to valuation based on these goals and describe an agenda for NC and ES measurement, valuation, and management within this broader framework.

## 2. Value systems, value, and valuation

The concepts of value system, value, and valuation have many meanings and interpretations and a long history in several disciplines (c.f. Costanza, 2004; Mazzucato, 2018). After this long and interesting history, the issue of value is now going through another period of rapid development that should help us to make better, and more sustainable, decisions, not only as individuals but also as groups, communities, and stewards of the entire planet. First, I want to lay out some basic definitions of value systems, value, and valuation that I hope are useful to this evolving development.

Value systems refer to intra-psychic constellations of norms and precepts that guide human judgment and action. They refer to the normative and moral frameworks people use to assign importance and

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**Table 1**
Valuation of ecosystem services based on the three primary goals of efficiency, fairness, and sustainability (Costanza and Folke, 1997, Costanza, 2000).

| Goal or Value Basis | Who Votes | Preference Basis | Level of Discussion Required | Level of Scientific Input Required | Specific Methods |
|---|---|---|---|---|---|
| Efficiency | *Homo economius* | Current individual preferences | Low | Low | Willingness to pay |
| Fairness | *Homo communicus* | Community preferences | High | Medium | Veil of ignorance |
| Sustainability | *Homo naturalis* | Whole system preferences | Medium | High | Modeling with precaution |

necessity to their beliefs and actions. Because value systems frame how people assign importance to things and activities, they also imply internal objectives. Value systems are thus internal to individuals but are the result of complex patterns of acculturation and may be externally manipulated through, for example, advertising.

There are two common but distinct meanings of "value:" (1) Things we think are important: i.e. "I value biodiversity" (but I may also value freedom, fairness, sustainability, income, and many other things); and (2) relative value incorporating tradeoffs: i.e. the value of protecting biodiversity is greater than the cost of protecting it.

Value in the first sense refers to goals or objectives. Value in the second sense refers to the contribution of an object or action to achieving specific goals, objectives, or conditions. The value of an object or action may be tightly coupled with an individual's value system because the latter determines the relative importance to the individual of an action or object *relative to* other actions or objects within the perceived world. However, people's perceptions are limited, they do not have perfect information, and they have limited capacity to process the information they do possess (Khaneman, 2011) so the connection between an individual's *perception* of an object or action's ability to achieve their goals and the reality of that connection may be very imperfect.

An object or activity may therefore contribute to meeting an individual's goals without the individual being fully (or even vaguely) aware of the connection. This may be especially important for supporting, regulatory and cultural ecosystem services, whose connection with individual's wellbeing may be not well perceived at all. The value of an object or action therefore needs to be assessed both from the subjective standpoint of individuals and their internal value systems and from the objective standpoint of what we may know from other sources about the connection. The standard economic definition of welfare is too narrowly based on individual, perceived, welfare assuming that people have full knowledge of what contributes to their welfare and that the welfare of society is simply the aggregate of individual welfare. Here I use wellbeing as a broader conception than individual perceived welfare. This conception recognizes that the sustainable wellbeing of individuals is more complex and multi-faceted than what they perceive and that the sustainable wellbeing of society is more than the aggregate of individual wellbeing. Sustainable wellbeing thus includes the wellbeing of individuals, society, and the rest of nature in complex interdependence. Therefore, valuation should also include contributions to broader societal goals in both the short term and the long term (i.e. sustainability).

Valuation is the process of assessing the contribution of a particular object or action to meeting a particular goal, whether or not that contribution is fully perceived by individuals. One can thus (and *must* if one hopes to be comprehensive and accurate) do valuation from multiple perspectives, using multiple methods (including both subjective and objective), against multiple goals. As discussed above, individual wellbeing is not the only goal. A broader conception of sustainable wellbeing includes the wellbeing of society and the natural ecosystems that support all life. Thus our goals for valuation need to include individual, societal, and ecosystem goals toward the overarching goal of sustainable wellbeing of humans and rest of nature – i.e. the whole earth system.

Costanza and Folke (1997) and Costanza (2000) described three types of value for ES and NC, based on the three sub-goals for sustainable wellbeing of humans and the rest of nature first articulated by Daly (1992) as:

1. sustainable scale – assessing and insuring that the scale or magnitude of human activities within the biosphere are ecologically sustainable – staying within planetary boundaries.
2. fair distribution – distributing resources and property rights fairly, both within the current generation of humans and between this and future generations, and also between humans and other species.
3. efficient allocation – efficiently allocating resources as constrained and defined by 1 and 2 above, and including both marketed and non-marketed resources, especially natural and social capital and ecosystem services.

Conventional economic 'willingness-to-pay" approaches are focused on the third of these goals using current individual preferences. But valuation with respect to the fairness and sustainability goals needs different approaches that are more in line with community or societal preferences and whole system ecological sustainability issues (Table 1). In addition, individual tastes and preferences are not fixed and given, as is usually assumed in conventional economic valuation (Norton et al., 1998), and individuals do not possess perfect information or appropriate processing abilities about the relationship between ES and their wellbeing, as is also assumed (Kahneman, 2011).

Thus, we can distinguish at least three types of value that are relevant to the problem of valuing ecosystem services. These are laid out in Table 1, according to their corresponding goal or value basis.

Efficiency based value (E-value) is based on a model of human behavior sometimes referred to as "*Homo economius*"— that humans act independently, rationally, and in their own self-interest. Value in this context (E-value) is based on current individual preferences, which are assumed to be fixed and given (Norton et al., 1998). No additional discussion or scientific input is required to form these preferences (since they are assumed to already exist), and value is simply people's revealed or stated willingness to pay for the good or service in question. The best estimate of what people are willing to pay is thought to be what they would actually pay in a well-functioning market. For resources or services for which there is no market (like many ecosystem services) a pseudo-market can sometimes be simulated with questionnaires that elicit individual's contingent valuation. As noted above, there are serious issues with these assumptions, since tastes and preferences are not fixed and given, and individuals do not possess perfect information or appropriate processing abilities about the relationship between ES and their wellbeing or the wellbeing of society, especially in the long term.

Fairness based value (F-value) would require that individuals vote their preferences as a member of the community, not as individuals (Costanza and Folke, 1997; Wilson and Howarth, 2002). This different species (*Homo communicus*) would engage in much discussion with other members of the community and come to consensus on the values that would be fair to all members of the current and future society (including nonhuman species), incorporating scientific information about possible future consequences as necessary. One potential method to implement this might be Rawls' (1971) concept of a "veil of ignorance," where everyone votes as if they were operating with no knowledge of their own individual status in current or future society.

Sustainability based value (S-value) would require an assessment of the contribution to ecological sustainability of the item in question. The S-value of ecosystem services is connected to their physical, chemical, and biological role in the long-term functioning of the global system. Scientific information about the functioning of the global system thus is critical in assessing S-value, and some discussion and consensus building is also necessary. If it is accepted that all species, no matter how seemingly uninteresting or lacking in immediate utility, have a role to play in natural ecosystems (Naeem et al., 1994; Tilman and Downing, 1994; Holling et al., 1995), estimates of ecosystem services may be derived from scientific studies of the role of ecosystems and their biota in the overall system, without direct reference to current human preferences. Humans operate as *Homo naturalis* in this context, expressing preferences as if they were representatives of the whole system. Instead of being merely an expression of current individual preferences, S-value becomes a system characteristic related to the item's evolutionary contribution to the survival of the linked ecological economic system (to the extent that we can understand it). Using this perspective, we may be able to better estimate the values contributed by, say, maintenance of water and atmospheric quality to long-term human well-being, including protecting the opportunities of choice for future generations (Golley, 1994; Perrings, 1994). One potential way to get at these values would be to use systems simulation models that incorporate the major linkages in the system at the appropriate time and space scales (Costanza et al., 1993, 2002; Bockstael et al., 1995, Boumans et al., 2002). To account for the large uncertainties involved, these models would have to be used in a precautionary way, looking for the range of possible values and erring on the side of caution (Costanza and Perrings, 1990).

There is therefore much additional work that needs to be done in valuing ES and NC, in individual, social, community, and group contexts. Conventional approaches can only get us part of the way.

Progress in this area is being made, often under the name of 'integrated valuation', and 'participatory valuation' where combinations of valuation methods are used to address the full set of values (Braat et al., 2014; Brown and Fagerholm, 2015; Jacobs et al., 2016; Kenter, 2016).

## 3. What units?

The relative value of ES is about trade-offs in contributing to the sustainable wellbeing and these trade-offs can be expressed in many ways and in many different units. These trade-offs may be perceived by individuals and reflected in their choices, but in many cases they are not. For example individuals would have a hard time perceiving the connection between the storm protection services of coastal wetlands and their wellbeing, unless these connections were studied by experts and communicated to them. The point is that the trade-offs exist whether people perceive them or not and a comprehensive, integrated approach to ES valuation must use all the information available in a more synthetic way.

If at least one of the items being traded-off is expressed in monetary units, we can express ES in those units as well. This has the advantage of being a unit that most people understand and one that can easily be used in various analyses. However, some confuse expressing trade-offs in monetary units with market-based valuation, privatisation or commodification of ES. This is really the opposite of what ES valuation in monetary units is about, since the majority of ES are non-rival, non-marketed public goods. However, ES can be expressed in other units if that is more appropriate and communicates better with the intended audience. These units can include: time, labour, energy, life satisfaction, or a variety of composite indices.

However, it should be clearly noted that our ability to understand, quantify, and value the full range of ES and NC is still fairly limited. There is (and will probably always be) a spectrum from relatively easily quantifiable to impossible to quantify given current knowledge. We need to acknowledge this spectrum and better incorporate the resulting uncertainty in decision processes, rather than ignoring the difficult to quantify items. We should acknowledge the degree of precision of our estimates but not throw out imprecise estimates. As Warren Buffett once quipped, "it is better to be approximately right than precisely wrong."

Finally, it is certainly true that some decision processes involving trade-offs do not seem to require valuation. A community may come to a consensus decision after deliberation and discussion of all the options without ever explicitly "valuing" the alternatives. The key word here is "explicitly." The decision itself implies valuation. However, if the decision process is better handled by keeping the valuation implicit, then why not? The point is that valuation has not been avoided, only explicit valuation has been avoided.

## 4. What about the intrinsic value of nature?

Intrinsic value refers more to the goal or basis for valuation and the protection of the "rights" of these goals to exist. For example, if one says that nature has intrinsic value, one is really claiming that protecting nature is an important goal in itself – it is something we value in the first sense as defined above. Relative values (in the second sense as defined above) are based on the contribution that something makes to achieving goals (directly or indirectly). One could thus talk about the value of an object or action in terms of its contribution to the goal of preserving nature. This is embedded in the idea of valuation based on the goal of sustainability as described above – i.e. the goal of protecting "nature". Some might argue that this is still a utilitarian or "anthropocentric" approach, since we humans are the ones establishing the sustainability goal. However, rather than implying that humans are the *only thing* that matters, the concepts of ecosystem services and especially the sustainability goal makes it clear that the *whole system* matters, both to humans and to the other species we are interdependent with. If anything, the ecosystem services concept is a 'whole system aware' view of humans embedded in society and embedded in the rest of nature. 'Centric' with any prefix doesn't really describe this complex interdependence (Costanza et al., 2017).

It is also important to recognize that the three sub-goals are not "either–or" alternatives. Whereas they are in some senses independent multiple criteria (Arrow and Raynaud, 1986), they must all be satisfied in an integrated fashion to allow human life to continue in a desirable way. Similarly, the valuations that flow from these goals are not "either–or" alternatives. Rather than an "utilitarian or intrinsic rights" dichotomy, we must integrate the three goals listed above and their consequent valuations.

## 5. Natural capital, ecosystem services, and sustainable wellbeing

The ecosystems that provide the services are sometimes referred to as 'natural capital,' (NC) using the general definition of capital as a stock that yields a flow of services over time (Costanza and Daly, 1992). Here the term 'capital' is useful to reconnect the human economy with its ecological dimensions and is not meant to imply that natural capital can or should be privatized or marketed in the way that built capital can be.

In order for these benefits to be realized, natural capital (which does not require human activity to build or maintain) must interact with other forms of capital that *do* require human agency to build and maintain. These include: (1) built or manufactured capital; (2) human capital; and (3) social or cultural capital (Fig. 1). Built capital and human capital (the economy) are embedded in society, which is embedded in the rest of nature.

These four general types of capital are all required in complex combinations to produce any human benefits. Ecosystem services thus refer to the relative contribution of natural capital to the production of

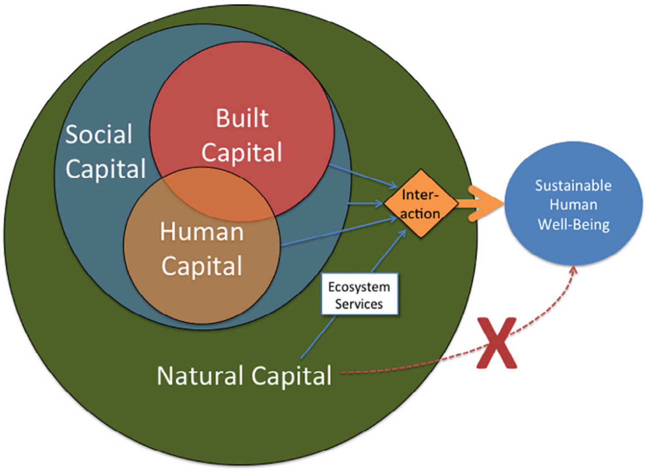


**Fig. 1.** The interaction between built, social, human and natural capital affects human wellbeing (Costanza et al., 2014b). The "*x*" implies that sustainable wellbeing does not flow directly from natural capital, but requires the interaction with the other 3 types of capital.

various human benefits, in interaction with the other forms of capital. These services do not simply flow to sustainable human wellbeing without these crucial interactions. As a consequence, understanding, modelling, measuring, and managing ecosystem services requires a very transdisciplinary, whole systems approach.

## 6. Improving the valuation of natural capital and ecosystem services

There have been several recent assessments of the status and trends in ecosystem services and their valuation (c.f. Gómez-Baggethun et al., 2010; Jacobs et al., 2013, 2016, Costanza et al., 2017). The challenge is improving and extending all three types of valuation described above (Efficiency (E), Fairness (F), and Sustainability (S) value) and better integrating them. Lets look at each of these in turn.

## 7. Efficiency (E) valuation

"Economic value" is often defined in strict economic terms as aggregate willingness-to-pay for the stream of services or to accept compensation for their loss. Hence, the narrowly defined economic value of an ecosystem function or service relates only to the contribution it makes to 'human welfare', where human welfare is measured in terms of each individual's own assessment of his or her wellbeing (Bockstael et al., 2000; Freeman, 2003). Most previous valuations of ES have been limited to this "efficiency based" valuation.

As discussed above, such a definition is far too narrow for the purposes of valuing natural capital and ecosystem services (Farber et al., 2002). ES are the direct and indirect contributions to sustainable human wellbeing, which includes, but is more than the aggregate of individual, self-assessed welfare. This is true because sustainable human wellbeing also depends on the welfare of the community or society, (*F*-value) and on the contributions and sustainability of the ecological life support system (*S* value). Also, as discussed above, individual humans do not adequately perceive all the things that contribute to their wellbeing. There is a huge literature criticizing the utilitarian willingness-to-pay model, (c.f. Pascual et al., 2010; Parks and Gowdy, 2013).

The research agenda here has to do with recognizing the problems with the underlying assumptions and being more realistic about how humans think, behave, express, and construct preferences (Tversky and Kahneman, 1981; Kahneman, 2011). The emerging fields of behavioural, experimental, and evolutionary economics are where we can find support for new approaches to E-valuation (Slovic, 1995; Camerer, 1999; Henrich et al., 2001; Thaler and Ganser, 2015). Can we develop better ways to estimate what values individuals would place on ES and NC if the assumptions of rationality, perfect information, and enlightened preferences and self-interest could be better approximated or if knowledge of actual behaviour in choice situations with limited information can be better simulated?

In addition, E-valuation is best suited to those ES that are private, excludable and rival goods (i.e. provisioning and some cultural services) since these are the ES that can be best handled with "market-like" revealed or stated preference approaches (Costanza, 2008). ES that are best described as public goods (i.e. regulatory and supporting services and some cultural services) are better handled with *F* and *S* valuation approaches as described below.

## 8. Fairness (*F*) valuation

When valuing those ES and NC that are largely public goods, we need a process that incorporates the community and the public, not just the aggregate of individuals. This requires deliberative processes and consensus building in a way that allows the science about ES and NC to be adequately incorporated (Wilson and Howarth, 2002, Mavrommati et al., 2017).

F-valuation approaches are needed that can acknowledge the variety of individual and group dimensions and incorporate better information about the dynamics of NC and ES at multiple geographical and temporal scales. Deliberative processes aimed at understanding, ranking, and quantifying the potential benefits of ES can help the community to value them as public goods that benefit the whole community leading to what some have called "shared values" (Kenter, 2016).

Operationalizing deliberative approaches to valuation has been progressing. (Wilson and Howarth, 2002; Howarth and Wilson, 2006; Kenter, 2016; Kenter et al., 2016). A major constraint is the time and effort involved in convening the appropriate groups. The internet may provide some help here. Rather than expensive face-to-face groups, online groups may be able to approximate the necessary deliberative processes. This is an exciting new research area.

## 9. Sustainability (*S*) valuation

*S*-Valuation requires an integrated, whole system approach at the appropriate spatial and temporal scales (Boumans et al., 2002; Costanza et al., 2002, Costanza and Voinov, 2003; Braat et al., 2014). For example, integrated, dynamic, spatially explicit computer modelling is increasingly being used as a tool to address the complexity of interactions that lead to ES production (Higgins et al., 1997; Boumans et al., 2002, 2015; Costanza and Voinov, 2003; Bagstad et al., 2013; Turner et al., 2016). One advantage of this approach is that it can potentially incorporate both perceived and non-perceived benefits in a dynamic way that allows for the evaluation of a range of policy scenarios in both the short and long term.

One interesting recent example that provides an indication of the complexity and temporal and spatial scale of what can be developed is a model of the ancient Maya civilization (Heckbert et al., 2014). This model was developed as part of an NCEAS participatory working group. The MayaSim model describes how anthropogenic and biophysical processes changed over time and space over a 600 year time period in the Yucatan peninsula. The model is a spatially explicit, hybrid, process-based, network, and agent-based model implemented in NetLogo.

In addition, integrated models can potentially become the basis for computer games that can engage players in decisions that can be the basis for understanding and valuation (Costanza et al., 2014c). Since integrated models can embed the trade-offs between, for example, better ecosystem services and more population and urban land use, the choices the players make will reflect how they value these trade-offs, in a dynamic way that will depend on initial conditions, and, in some games, interactions among players. This is like a conventional choice experiment (Wilson and Carpenter, 1999; Colombo et al., 2013), except that it allows the players to create their own scenarios, rather than presenting them with a fixed set. It also allows preferences to emerge as a result of learning about the system by playing it and though interactions with other players. By playing the game, they are also becoming informed about the trade-offs in a much more tangible way than simply being told about them. The system thus connects the best of choice experiments, social interaction, and dynamic modelling. By recording each player's behaviour in the system, one can also build computer agents that behave more like real people.

A major constraint to this approach is the time and effort required to build, calibrate, run, debug, and employ the models. Technical advances in computer systems, modelling software, and big data availability are all coming together to improve the feasibility of this approach to ES modelling and valuation and this is an active and expanding research area.

## 10. Integrated valuation

Ultimately, all three of these components to valuation should be integrated. E-valuation is needed for private goods, but there is still much to be done to improve how it is done. F-valuation is needed to bring in community values for public goods and we need better, more cost-effective ways of doing this. S-valuation is needed to bring in complex, long-term ecosystem and social dynamics and patterns and we can build integrated computer models to help with this. But all three of these components can potentially be brought together in integrated valuation exercises that include individual surveys, group deliberative processes, and integrated computer modelling and gaming. The internet may provide a huge opportunity to improve this integrated approach.

## 11. Property rights, PES, and common asset trusts

Once we have done the appropriate valuation exercises, how can they best be used?

Given the public goods nature of most ecosystem services, we need institutions that can effectively deal with this characteristic using a sophisticated suite of property rights regimes. We need institutions that employ an appropriate combination of private, state, and common property rights systems to establish clear property rights over ecosystems without privatizing them.

The basic idea behind common property rights is that resources created by nature or society as a whole should belong to all of us, including future generations. The misleadingly labeled 'tragedy of the commons' (Hardin, 1968) results from no ownership or open access to resources, not common ownership. Abundant research shows that resources owned in common can be effectively managed through collective institutions that assure cooperative compliance with established rules (Feeny et al., 1990; Berkes, 1989, Ostrom, 1990, 2002; Atkins et al., 2019). Ostrom has articulated 8 core design principles for effective and sustainable commons management (Ostrom, 2002). The first of these is that there must be "clearly defined boundaries" – in essence common property rights held by the community as a whole.

By declaring certain assets the shared property of all members of the community, the community of beneficiaries has clearly defined boundaries, and all members will have an incentive to monitor their fellows and ensure that no individuals take what belongs to all. Those who do take more than their share are likely to be first rebuked by their compatriots, and if rebuke fails, reported to the law—an example of *graduated sanctions*. As Wilson et al. (2013) note, when citizens have "a sense of ownership, monitoring and graduated sanctions take place spontaneously." (p. 529).

When a resource is non-rival and non-excludable (or rival but non-excludable), it can thus be 'propertized' (which is to say, made excludable) to prevent over-use. Governments (or in the case of global resources such as atmospheric waste absorption capacity or oceanic fisheries, a coalition of global governments) are generally required to create and enforce property rights. For example, the public sector can cap resource use at rates less than or equal to renewal rates, which is compatible with inalienable property rights for future generations. Since the resources under discussion were created by nature and enforcement of property rights requires the cooperative efforts of society as a whole, rights to the resource should also belong to society as a whole. Individuals who wish to use the resource for private gain should compensate society for the right to do so. For example, a cap and auction scheme, in which the revenue is shared equally among all members of society, or else invested for the common good works this way (Barnes et al., 2008). Taxes on waste emissions and resource extraction can serve the same purpose as a cap and auction system. Preventing the re-sale of the temporary use-rights would reduce the potential for speculation and private capture of rent.

Under common ownership, both costs and benefits accrue to society as whole, and the two are more likely to be brought into balance. This satisfies Ostrom's second core design principle – that there be proportional equivalence between benefits and costs. Cap and auction schemes ensure that everyone who uses common assets must pay the same price, with resulting revenue spent on the common good, while taxes on rent ensure that no one captures unearned profits from common assets. Both policies ensure that the core design principle of *equitable distribution of contributions and benefits*, is met.

Systems of payment for ecosystem services (PES) and common asset trusts can be effective elements in institutions that implement common property regimes (Farley and Costanza, 2010; Sattler and Matzdorf, 2013). PES is defined as payments to land owners or managers to provide or protect ecosystem services. When a resource is non-rival, excludable private property rights are inappropriate, but lack of property rights leads to overuse (Kubiszewski et al., 2010). One solution is common investment and common use. Common asset trusts (CATs) are one institution that can assign property rights to the commons on behalf of the community, using trustees as protectors of the asset (Barnes et al., 2008; Farley et al., 2015). The CAT can charge for damages to the common asset and invest in the provision of non-rival ecosystem services and in green technologies that help provide and protect the asset. Everyone would be free to use the non-rival ecosystem services, but not to degrade the ecosystem structure that sustains them. Resources for investing in non-rival resources can be obtained from auctioning off access to rival resources. For example, society could auction off the right to greenhouse gas absorption capacity and then invest the revenue in carbon-free energy technologies and ecosystem restoration (Barnes et al., 2008).

## 12. Conclusions

While the *concepts* of natural capital and ecosystem services have been broadly accepted and their contribution to better environmental management widely acknowledged (MEA, 2005; Sukhdev et al., 2010; UK National Ecosystem Assessment, 2011; Díaz et al., 2015), practical applications are still limited. Limiting factors include: (1) inconsistent approaches to NC and ES modelling, assessment and valuation; (2) the expense of applying sophisticated enough methods to adequately answer the questions; and (3) the lack of appropriate institutional frameworks. These limiting factors are rapidly being removed. Broad application of the Efficiency, Fairness, and Sustainability (EFS) valuation framework described in this article in an integrated way could provide a more sophisticated approach, grounded in sound ecosystem science, psychology, and behavioural economics, that can be consistently applied in the appropriate institutional frameworks at relatively low cost. The development of this approach will require a sustained effort, one that is already underway by ecosystem services researchers and practioners around the world, but it still has a long way to go.

Better *E*-valuation can incorporate what we are learning about human psychology and choice behaviour (Kahnemann, 2011). It can, recognize that preferences are not fixed and given, but respond to external stimuli and information (Norton et al., 1998) and are usually *constructed* in the process of decision-making (Slovic, 1995; Warren et al., 2011).

Better *F*-valuation can fully utilize deliberative processes by working to overcome the constraints that prevent face to face deliberation. This will most likely require better use of the internet and rapidly evolving software applications that allow effective deliberation among physically (and temporally) dispersed participants.

Better *S*-valuation can incorporate rapidly advancing big data and integrated modelling tools and capabilities (Boumans et al., 2002, 2015; Victor, 2018). This can be combined with *F*-Valuation via the use of participatory modelling in which the full range of stakeholders work together to conceptualize, run, and interpret the models (van den Belt, 2004; Voinov et al., 2016). These models can also be used as the basis for "useful games" to engage much broader participation in the use of the models while at the same time serving as a research tool for exploring user's values and valuation decisions (linking with *E*-valuation) and educating a broader public about ecosystem services and their connection to sustainable human wellbeing and how it is connected to the wellbeing of the rest of nature (Costanza et al., 2014c)

Each of the three elements of EFS valuation continue to make progress, and their integration is also making progress. There are many policy decisions (including PES and CATs mentioned above), whose implementation requires a cohesive and holistic approach – from estimates of the magnitude of values, to institutional arrangements with clear roles and responsibilities with respect to regulation, assessment, implementation, monitoring, and enforcement. Integrated EFS assessment and valuation can contribute to improving this process.

But the systems we are modelling and valuing are very complex and we should not expect to ever reach the end of this quest. As George Box famously said: "all models are wrong, but some are useful." Our goal is to improve the utility of our models of natural capital and ecosystem services in order to better achieve our ultimate goal of a sustainable and desirable future for humans and the rest of nature.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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