Stocks and flows of natural and human-derived capital in ecosystem services

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Published in:
Land Use Policy

Publication date:
2016

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Abstract

There is growing interest in the role that natural capital plays in underpinning ecosystem services. Yet, there remain differences and inconsistencies in the conceptualisation of ecosystem services and the role that humans play in their delivery. Using worked examples in a stocks and flows systems approach, we show that both natural capital (NC) and human-derived (produced, human, social, cultural, financial) capital (HDC) are necessary to create ecosystem services. HDC plays a role at three stages of ecosystem service delivery. Firstly, as essential elements of a combined social-ecological system to create a potential ecosystem service. Secondly, through the beneficiaries in shaping the demand for that service. Thirdly, in the form of additional capital required to realise the ecosystem service flow. We show that it is possible, although not always easy, to separately identify how these forms of capital contribute to ecosystem service flow. We discuss how applying a systems approach can help identify critical natural capital and critical human-derived capital to guide sustainable management of the stocks and flows of all forms of capital which underpin provision of multiple ecosystem services. The amount of realised ecosystem service can be managed in several ways: via the NC & HDC which govern the potential service, and via factors which govern both the demand from the beneficiaries, and the efficiency of use of the potential service by those beneficiaries.

Keywords

Natural capital; human capital; scale; sustainable; beneficiaries; potential service

Highlights

- Realised ES are a product of the potential service and specified beneficiaries.
- Natural capital (NC) and human-derived capital (HDC) are both essential for ES.
- HDC plays a role even at the stage of potential ecosystem services
- Sustainable management should identify critical NC and HDC for each service.

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1 Introduction

Within the ecosystem services literature there is an emerging focus on natural capital (TEEB 2013), the components of natural systems that underpin the delivery of ecosystem services. This is driven partly by concern at national and global scales that stocks of natural capital are being used at an unsustainable rate (Hails and Ormerod, 2013), and partly by the development of green accounting frameworks or the desire to separate the added value provided by human inputs from that contributed by the natural environment (UKNEA 2011; Bateman et al. 2011; Remme et al. 2014; Schröter et al. 2014a). Yet, despite this focus, definitions of natural capital remain varied (e.g. Dickie et al. 2014). The role of human capital in the supply and delivery of ecosystem services is increasingly recognised (Tallis et al. 2012; Remme et al. 2014; Burkhard et al. 2014), and within the Ecosystem Approach humans are seen as part of an interactive holistic (socio-economic) system, where the welfare of humans and the health of the natural world are co-dependent (Raffaelli & White 2013). However, uncertainty remains about the extent to which human capital contributes, and at which stages in the process of delivering ecosystem services it plays a role. If these concepts are to be useful for decision makers, they need to better integrate evidence on natural resource availability with an understanding of how society interacts with those resources (Olsson et al. 2004) in clearly defined ways.

In this paper we discuss two key issues in current thinking on the role of natural and human capital in delivering ecosystem services, and tie together emerging literature on these issues: 1) the conceptualisation of how ecosystem services are delivered; 2) the relative contribution of human and natural capital to ecosystem services delivery. We use examples of provisioning, regulating and cultural services delivered in multi-functional landscapes to illustrate a clarified understanding of ecosystem service delivery. Recognising that many stocks of capital are not being utilised or managed sustainably, we discuss the implications for better long-term management of stocks of natural and human capital. These ideas have arisen through discussions among a multi-disciplinary team involving natural scientists, social scientists, economists, NGO representatives, government policy makers and land managers.

2 Current issues

Most ES frameworks illustrate a linear-cyclic view where the environment provides a range of ecosystem services, from which humans obtain goods or benefits to which a value can be attached (e.g. MA, 2005; TEEB 2010; Maes et al. 2013), with the role of natural capital more recently defined as underpinning ecosystem service delivery (TEEB 2013). The cycle typically goes on to describe management feedbacks in response to human and other drivers of the system which in turn affect the natural environment (van Oudenhoven et al. 2012). In this paper, we explore particularly the part of this cycle concerned with generation or production of ecosystem services and the role of people in this process. We argue that portraying humans simply as users of natural capital or ecosystem services is an over-simplification impeding our conceptual understanding of how ecosystem services are delivered and, as a consequence, the management of ecosystem service delivery and associated stocks of natural capital. Two issues emerge from this discussion:

1) Although consensus is starting to emerge among the ecosystem services research community, there is a lack of clarity among many environmental scientists and policy makers in the conceptualisation of how ecosystem services are delivered. This applies to the majority of services, but perhaps more so in the case of cultural services for which typologies are still evolving (Daniel et al. 2012; Chan et al. 2012a,b; Brown 2013; Church et al, 2014; Kenter et al, 2014). Many environmental scientists see ecosystem services purely from an ecosystem perspective, and fail to appreciate that services are defined in the context of their use by humans. Meanwhile, the linkages which establish how ecosystems provide a service that is subsequently used by beneficiaries also remain poorly defined for the majority of services. This lack of clarity has hindered the development of integrated approaches to ecosystem service quantification and modelling.

2) While it is accepted that humans are part of the environment (Raffaelli & White, 2013), it is not always recognised that they perform multiple roles in an ecosystem services framework, e.g. as co-producers of ecosystem services, as beneficiaries of those services, and through the addition of capital to realise those services. Those roles are currently ill-defined. There is also a desire to separate out the natural capital and human capital elements of ecosystem service provision, driven by the needs of environmental asset accounting with its focus on natural capital (TEEB 2010, Remme et al. 2014), and by a desire for economic valuation of goods and benefits (Boyd & Banzhaf 2007). However, improvement is needed in identifying the range of components that go to make up a service, and distinguishing between the role of humans as beneficiaries of services, and their role in contributing to the service itself at multiple points along the ecological production function and the economic production function. Using a systems approach, we show that it is possible to separately identify how both natural and human-derived capital contribute to ecosystem service delivery for the three categories of final ecosystem services (*sensu*. Fisher et al. 2008): provisioning, regulating and cultural.

There is increasing recognition that many stocks of natural capital are not being utilised or managed effectively, and their rate of use is not sustainable. At a global scale this rate of resource use may lead to exceedance of planetary boundaries (Steffen et al. 2015). At local scale unsustainable resource use has more immediate consequences for human wellbeing, along with equity issues in terms of access to ecosystem services, and may be a key consideration in evaluating trade-offs among ecosystem services in land management or policy decisions. Therefore, we explore how an improved understanding of how ecosystem services are produced, and the role of humans in that process can help guide sustainable management of these stocks into the future.

3 Issue 1. How are ecosystem services delivered: Potential and realised services, the role of people as users of ecosystem services

The concept of ecosystem services is an acknowledged anthropocentric construct and their very definition centres on what the environment provides for humans (MA, 2005). Without users or beneficiaries (subsequently termed ‘beneficiaries’) the service does not exist. The way that this relationship between society, economy and nature is expressed in the ecosystem services construct is significant – for example riparian woodland may slow overland flow of water into streams, attenuating a flood peak, but if there is no community downstream which benefits from reduced flooding then that function does not constitute a flooding-regulation service within an ecosystem services framework. Schröter et al. (2014a) and Bagstad et al. (2014) provide good examples of this.

For a service to be realised therefore, there needs to be not only a set of products, functions or processes provided by the ecosystem but a corresponding set of beneficiaries which derive a service from them, illustrated simply in Figure 1. This makes clear the distinction between what we call the ‘potential ecosystem service’ provided by the ecosystem, similar to what Tallis et al. (2012) describe as service ‘supply’ and Schröter et al. (2014a) and Villamagna et al. (2014) term ‘capacity’, and the service that is actually used by humans, that is the ‘realised ecosystem service’, akin to ‘service flow’. It is generally accepted now that to accurately characterise and quantify a particular service, the beneficiaries need to be precisely defined (Bagstad et al. 2013). For example, a lake or reservoir can provide water supply for both irrigation and for drinking. However, those two uses of water supply have discrete subsets of beneficiaries with different characteristics in terms of spatial location and water quality requirements. Taken further, the quantity of service that is realised must also be determined by the beneficiaries. For a given attenuation of a flood peak provided by the land use in a catchment, if the urban population expands in the flood-prone area, or new critical infrastructure such as an electricity sub-station is built, then the level of realised service increases.

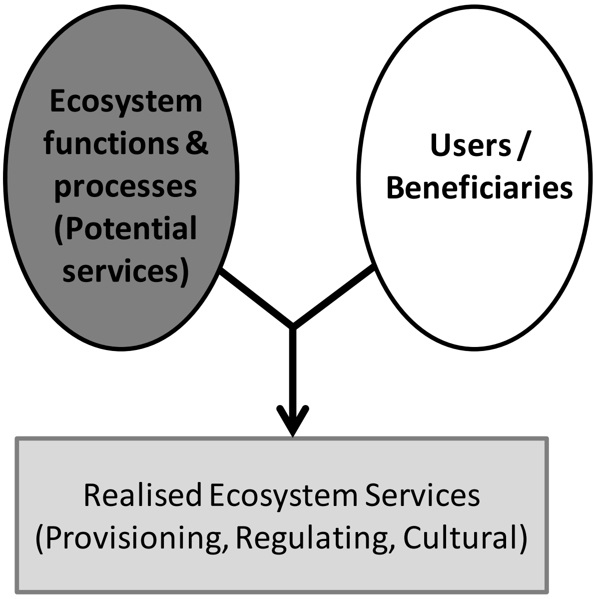

Figure 1. Potential service supply and beneficiaries are both necessary to define the realised ecosystem service.

This clarification helps to define what is meant by the flow of an ecosystem service, which is the amount of service realised by beneficiaries (Schröter et al. 2014a; Villamagna et al. 2014). We make a distinction here between the realised ecosystem service flow and the flows of capital (material or information) which contribute to the potential service, discussed in detail in section 4. The amount of realised ecosystem service flow is a function of the amount of potential service that can be provided (potential supply), the number of beneficiaries and their service needs (user demand), and their efficiency of use of the service (Figure 2a). The realised service flow can be constrained by inadequate supply, i.e. there are more potential beneficiaries than the potential service can support and there is unmet demand (Figure 2b), or constrained by insufficient beneficiaries, i.e. there is unused potential service (Figure 2c). The amount of realised service flow can also be increased without changing the amount of potential service by careful management or improvement of the way the service is delivered (Figure 2d). This can be achieved by altering the properties or characteristics of the potential service, the beneficiaries, or the way in which they interact, and is discussed further in section 5.

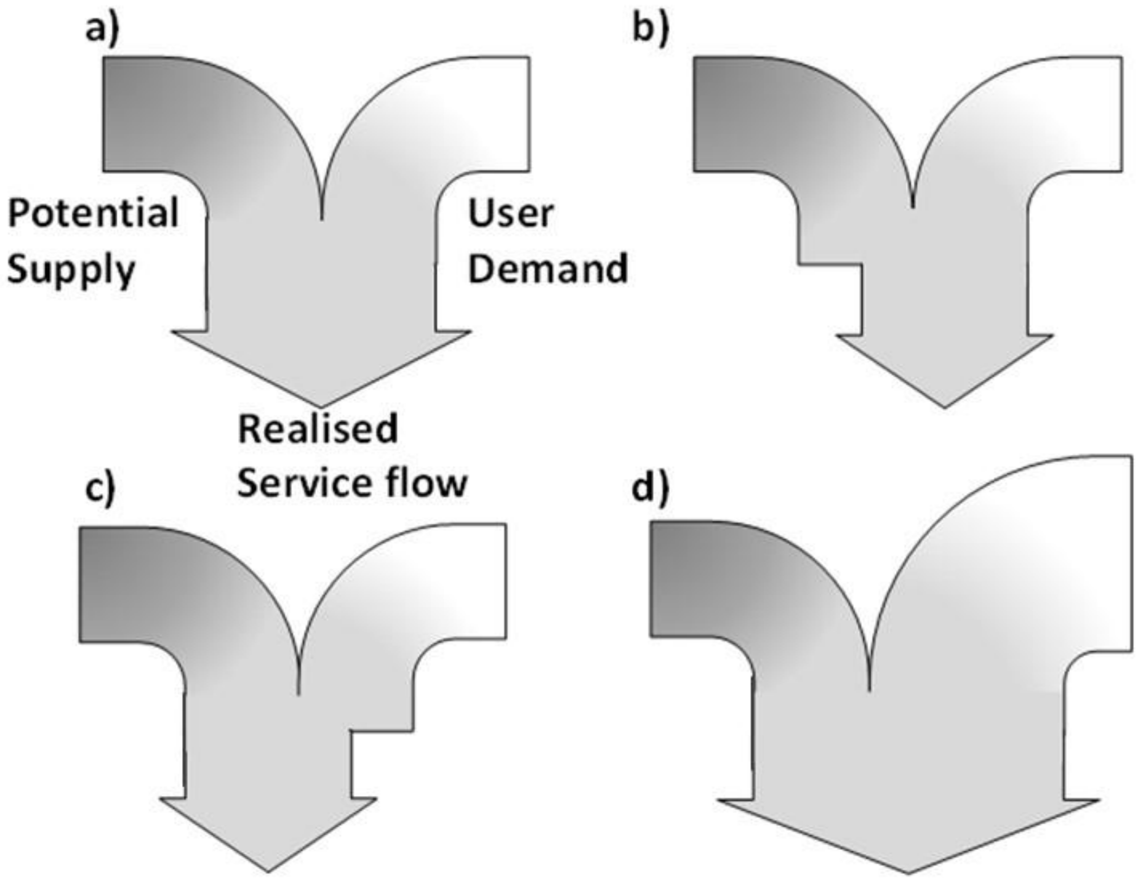

Figure 2. Conceptualisation of how potential service (supply) and user demand combine to determine the quantity of realised service flow (a). Changes in the amount or efficiency of both supply and demand affect the magnitude of service flow: b) Service flow is constrained by inadequate supply; c) Service flow is constrained by insufficient user demand, i.e. there is unused supply; d) efficiency of use is increased therefore service flow increases despite supply remaining constant.

This has implications for how we quantify or measure service delivery, particularly in the context of sustainable management of ecosystem services into the future (Eigenbrod et al. 2011; Villamagna et al. 2014). To illustrate with an example, the residents of a town situated in a low-intensity mixed agricultural landscape use a cultural service which we call 'visual appreciation of landscape'. As the population increases and the town slowly expands into that landscape, the potential service declines since there is less visually-appealing agricultural landscape overall. However, the number of beneficiaries of course goes up meaning that the total realised service might increase. If we further seek to value that service (using monetary or non-monetary measures) the value may go up or down for a range of reasons, including the socio-economic status and value systems of the beneficiaries. In order to manage this service sustainably into the future it is necessary to capture all three elements of change in the service:

- Amount of potential service, in this case the area of agricultural landscape and the quality of its characteristics which together define the level of potential service.

- Beneficiaries of the service, most easily quantified as the number of people, but more sophisticated metrics may be applied.
- Value of the service. This may be described in monetary or non-monetary terms, and will be dependent on the way that the beneficiaries of the service are defined and quantified.

This example illustrates that calculating the value of ecosystem services alone, whether through markets or non-market valuation is not sufficient to assess whether capital is being used sustainably and does not support an Ecosystem Approach (Norgaard, 2010; Scott et al. 2014). Markets capture only demand in relation to supply, not the long term future of the capital, and other measures of value rarely capture issues of sustainability. All three elements are needed in order to understand what aspect of ecosystem service delivery is changing and why. Capturing multiple aspects of ecosystem service delivery for each service will make analysis of trade-offs among services more complex, but is necessary for sustainable management.

In summary, we define the potential ecosystem service as that provided by the ecosystem before it is used by beneficiaries, at which point it becomes a realised ecosystem service. The realised service equates to the ecosystem service flow, whose quantity is a function of the amount of potential service, the number and characteristics of beneficiaries, and the efficiency with which they use the service. Quantifying ecosystem services to inform sustainable management and trade off analysis should therefore aim to capture information on the potential service, the realised service used by beneficiaries, as well as the economic value of that service.

4 Issue 2. The role of natural and human-derived capital in the delivery of ecosystem services

4.1 Context

Definitions of ecosystem services initially framed humans purely as users of the benefits provided by the environment. Recent frameworks (e.g. TEEB 2010; 2013; UKNEA 2011) incorporate humans within or interacting with a combined social-ecological system, but without specifying their respective roles. Others (Tallis et al. 2012; Spandenberg et al. 2014; Fisher et al. 2013; Burkhard et al. 2014; Remme et al. 2014) go further to highlight both the use of services from the environment, and some interaction between humans and the environment to deliver ecosystem services, although this is often confined to the cultural services. However, the reality is arguably more complex, and there is debate about both the anthropocentric framing of the ecosystem services concept and the role of humans within it (Spash 2009). Increasingly across the globe, landscapes illustrate the connection and inter-dependence between human society and nature, and have been co-produced through a relationship between the two (Gorg 2007, Matthews and Selman 2006). This combined natural and human setting is more accurately described as a social-ecological system (Berkes et al. 2002; Olssen et al. 2004; Ostrom and Cox 2010). To a great extent, all three types of final ecosystem service: provisioning, regulating and cultural services are 'co-produced' by the environment and people, even at the stage of potential service supply. This is because, over much of the globe, the landscape is so modified by humans in terms of altered natural processes, agricultural practices and with large-scale infrastructure, that continued human intervention and management of natural capital are necessary for the delivery of many ecosystem services. The challenge from an ecosystem services perspective is to capture this element of co-production. Contrasting with this idea of co-production is the increasing desire to separately identify the elements of natural and human-derived inputs for green accounting or for valuation. We seek to address this challenge by clearly identifying the roles of natural and human-derived capital stocks and flows within a consistent framework, building on the clarified understanding of the elements required for an ecosystem service to occur, outlined previously.

4.2 Types of capital

Here we adapt the classification associated with the Sustainable Livelihoods Approach (SLA) (Carney, 1998; Solesbury, 2003), which considers five types of capital: natural, human, produced, social and financial. We add a sixth 'cultural' capital, and provide some definitions below. We use the term 'human-derived capital' to encapsulate produced, human, social, cultural and financial capital, as distinct from natural capital.

Natural capital has been variously defined as the stock of physical assets in the environment (water, trees, minerals, species, etc.), but also the processes (e.g. water purification, climate regulation) from which we obtain benefits (e.g. NCC 2013). Wider definitions (e.g. Daily et al. 2000), which include whole ecosystems, cause difficulties when trying to understand how the natural components combine with other, human-derived inputs to produce ecosystem services, and fail to recognise how the quality of capital also affects the ecosystem services produced. In this paper we define capital 'stocks' as being assets in the environment and capital 'flows' as transformations or movement of those stocks. We adopt an encompassing definition of natural capital as "A configuration (over time and space) of natural resources and ecological processes that contributes through its existence and/or in some combination, to human welfare" (Dickie et al. 2014). We discuss below how knowledge of their characteristics and the interactions between natural capital stocks and flows is essential in order to understand not only how services are delivered but how they might be managed sustainably. The distinction between natural and human-derived capital is not clear in the context of domesticated plants and animals. We use the term **cultivated natural capital** (Daly et al. 2005) to include crop cultivars and livestock breeds, a term which has also been applied to green infrastructure such as city parks.

Human-derived capital, is an umbrella term encapsulating the following forms of capital:

Produced capital, also called built, manufactured or reproducible capital consists of manufactured assets, such as roads, vehicles, houses, machinery, etc. **Human capital,** defined as the productive capacity of human beings and encompasses the stock of capabilities held by individuals such as knowledge, education, training, skills as well as physical and mental characteristics like behavioural habits and physical and mental health. **Social capital** which refers to the stock of contacts, trust, reciprocity and mutual understanding associated with social networks. It includes both 'bonding' social capital which consists of accumulated social relationships and bonds of trusts within a tight-knit, closed social group, and 'bridging' social capital which consists of relationships of trust in heterogeneous, open groups and between groups (Swendsen & Swendsen, 2009). **Cultural capital** which refers to the broader factors that allow us to interact with each other and the environment, including values and beliefs, socially held knowledge as well as socio-political institutions (Bourdieu, 1986; Berkes and Folke 1994; Cochrane, 2006). **Financial capital**, which is money that facilitates the interaction of other forms of capital by funding the activities that might be required for the services to be realised, managed, or improved.

All these different 'capitals' – natural, produced, human, cultural, social and financial – combine together in a way that in the social sciences is termed 'co-production'. That is, they are interdependent and changes in the properties of one can and do elicit changes in the others. Conceptually, these can be brought together as shown in Figure 3, where potential service supply is dependent on interactions between forms of natural capital and forms of human-derived capital as defined above, prior to becoming a realised ecosystem service through its use by beneficiaries. The quantity of service flow for some services is dependent on interactions between beneficiaries and the potential service, represented by the double-headed arrow.

This approach distinguishes clearly three places where human inputs in the form of human-derived capital are necessary for a service to occur in managed landscapes. i) As direct inputs to the social-ecological system which are necessary for a potential ecosystem service to occur (equivalent to the ecological production function), ii) On the demand side (Tallis et al. 2012) in the role of humans as beneficiaries shaping demand for the resulting service, and iii) As further inputs of human-derived capital necessary to realise the flow of the ecosystem service (as part of the economic production function), e.g. through the pipeline required to get drinking water to the beneficiaries. It therefore makes clear that some forms of human capital input are required for the potential ecosystem service to exist, as well as on the demand-side. This concept is discussed in more detail using examples in section 4.4, in which the natural and human-derived elements are separately identified for three types of final ecosystem service.

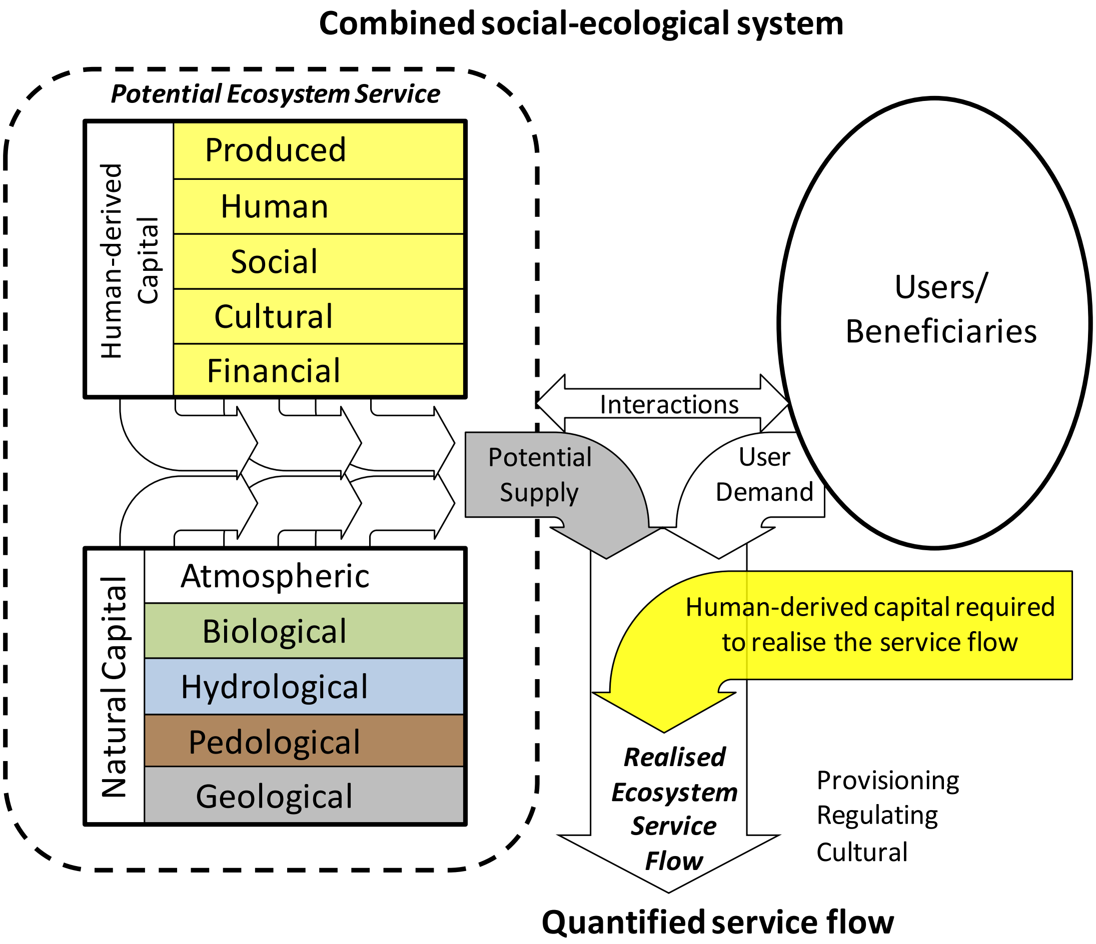

Figure 3. Different forms of human-derived capital and natural capital (subdivided after Robinson et al. (2013)) co-produce potential ecosystem services, which in combination with demand from users/beneficiaries then produce a flow of 'realised' ecosystem services.

4.3 The building blocks required for a systems approach

Having set the context, we now explore in more detail the relationship between stocks and flows of natural capital and human-derived capital and the production of ecosystem services. To do this, we define a set of basic building blocks or elements which can be used in combination to represent any type of ecosystem service, and understand its properties. Subsequently we discuss how these elements can be combined to produce models of how ecosystem services are delivered using three different examples: one each from provisioning (maize production), regulating (flood control) and cultural (recreational walking) services. Note that the examples used here relate to final ecosystem services, but are equally important in underpinning supporting services, which also depend to an extent on both natural and human-derived capital. The basic building blocks are defined below:

Stocks are a quantifiable amount of material or information, with units for natural capital stocks often defined in a spatial context. Examples of stocks of natural capital include: soil organic matter quantified in grams per metre square; volume of water in a reservoir quantified in cubic metres. Some stocks of human-derived capital can be harder to quantify than others, but examples include: a social network of people who like to do recreational walking (hiking) quantified in number of individuals and their network connections (social capital); knowledge held by farmers about the fertiliser requirements of different crop varieties (human capital). **Composite stocks** can be measured (e.g. a stock of soil, quantified in tonnes, or centimetres soil thickness) but can also be subdivided and quantified as separate constituent stocks (e.g. for soil: particulate matter, air, water).

Flows into or from stocks represent an amount of matter or information defined in a spatial and temporal context, i.e. a quantity per unit area per unit time. As with stocks, there are natural flows (e.g. weathering rate representing a flow of minerals from bed-rock to soil quantified in Moles per square centimetre per second; rainfall amount as millimetres per year) and human-derived flows (e.g. flows of information from farmer to farmer on the best form of pesticide to deal with aphids). These flows of capital are distinct from the concept of realised ecosystem service flows of final ecosystem services, defined in section 3 above.

In addition to the quantity of stocks and their flows, we further define system **properties**, which consist of the attributes or characteristics of the system. They can be properties of the stocks themselves, or relate to their **spatial and temporal arrangement** in the system, which in various combinations determine the **quality** of the stock, and thereby its capacity to provide a service - see also definitions of structure metrics in Syrbe & Walz (2012). The specific attributes which define the quality of the stock will vary depending on the context and the use that the stock is being put to. These can also be quantified, but since they are more complex, their description will be elaborated below in the context of the individual service examples presented. Some relationships are not easily categorised as stocks, flows or properties. We call these **dependencies**, represented by arrows, showing where part of the system influences another, without a flow of capital necessarily occurring.

4.4 Exploring the issues in the context of examples

We use three examples to visualise these concepts and to draw out some of the nuances of applying this framework to particular contexts: maize production (Figure 4), river flood regulation (Figure 5), and recreational walking (Figure 6). The examples are set within a hypothetical mixed agricultural landscape, but the principles apply to many other social-ecological settings, and other ecosystem services.

4.4.1 Distinguishing natural capital and human-derived capital contributions to the delivery of potential ecosystem services

In all three examples, the essential role of human-derived capital in the creation of potential ecosystem services becomes clear using this approach. For maize production (Figure 4), the elements of natural capital include stocks of soil water and soil nutrients, with input flows of other natural elements of rainfall and solar energy. However, these are augmented by human-derived capital at all stages in the production of a crop. Produced capital is necessary to cultivate the land in the first place in the form of field-drains, or machinery to clear the land, plough, sow and manage the crop. For most crops, stocks of soil nutrients are supplemented by inputs of produced capital in the form of inorganic fertiliser. In some maize-growing areas soil moisture stocks are supplemented by irrigation, which could be defined as a flow of the natural capital of river water or groundwater made possible by the produced capital of the irrigation infrastructure. Other forms of human-derived capital include cultural capital such as the knowledge held by farmers about how to grow a crop; social capital such as the sharing of information and co-operation through formal (e.g. extension workers, agribusiness sector workers) and informal (e.g., family, other farmers) networks; and, not least, the developed crop seed varieties sown in the field, which comprise 'cultivated natural capital'. By analogy with standing timber in a forest or plantation, the specified potential service in this case is the production of a standing crop of maize, the realised service is harvested maize for human consumption.

In the flood regulation example (Figure 5), in addition to the natural capital elements of rainfall, soils, fields and river channels and wetlands, produced capital has a bearing on flood regulation in the form of field drains, walls and ditches. Human-controlled flows such as water abstraction from groundwater or rivers and irrigation of fields also impact on stocks and flows of water in the landscape. In the example of recreational walking (Figure 6), the natural capital elements include the landscape itself, and its component stocks of trees, fields, water bodies etc. These are complemented by a substantial contribution from human-derived capital which may, in many cases, be necessary for the service to occur. This comprises produced capital such as footpaths, car parking and access points, and elements of cultural and social capital which contribute to walking such as social acceptance of recreational walking as a meaningful and enjoyable activity, a safe environment in which to do so, the existence of clubs or societies for like-minded people to join, availability of literature, arts, and media around walking, and cultural institutions such as rights of way.

Delving deeper into the recreational walking example reveals that identifying the natural and human-derived capital elements which go to provide a service is non-trivial, neither is it easy to separate those factors that are necessary for the potential service to occur from those that determine the amount of realised service. It could be argued that no human capital is actually required for recreational walking in remote wilderness areas, but in practice the vast majority of recreational walking takes place in a context which includes footpath networks which are managed and maintained, with supporting infrastructure that includes car parking areas, route information, and may also include facilities such as toilets, and refreshment areas. We suggest that these elements are necessary to fully define the potential service, since they are pre-requisites for most people to decide whether to go walking, and where.

The descriptions above have focused on the human-derived capital required for the potential service to exist, but as shown by the yellow arrows to the users/beneficiaries, some human-derived capital plays a role in regulating demand for the service and, as shown by the large yellow arrow coming at the end of the chain, large amounts of human-derived capital are often required to realise the ecosystem service flow. It is this component which is typically referred to as the human capital inputs in most frameworks of ecosystem service delivery. Examples are machinery to harvest the crops, flood defences to further alleviate flooding, or transport infrastructure which facilitates access to recreation areas.

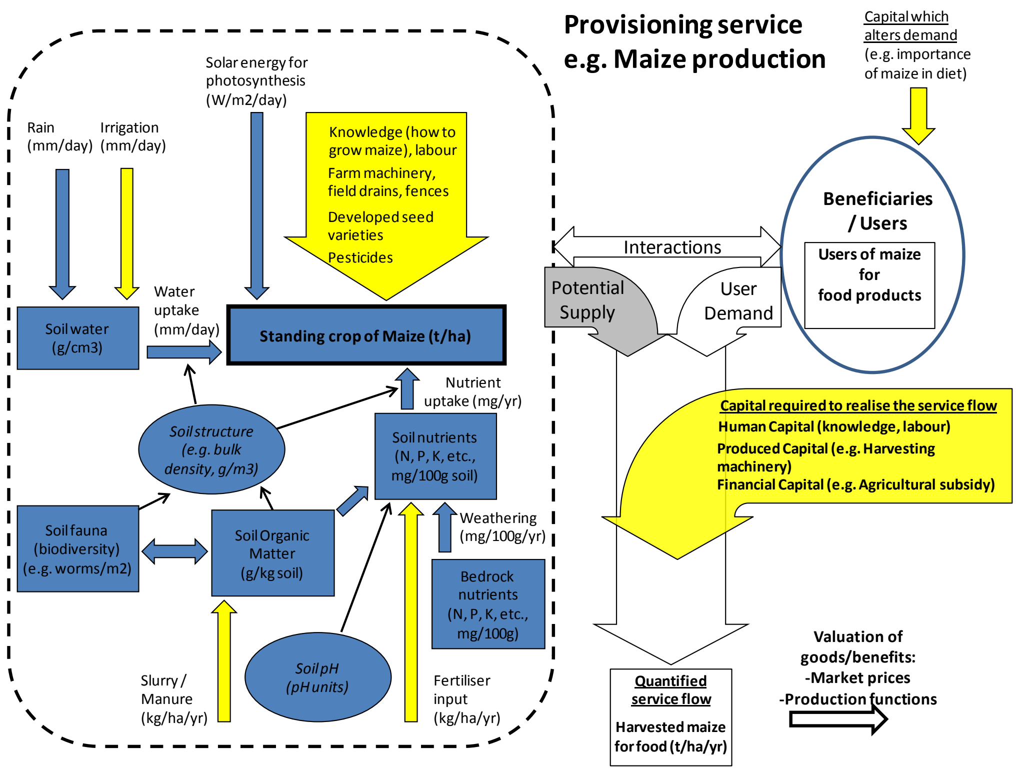

Figure 4. Simplified diagram showing natural and human capital inputs to a provisioning service: maize production. The potential service is production of a standing crop of maize, the realised service is harvested maize for human consumption. Key: Rectangular boxes = stocks, Ovals = other system components/properties, Solid arrows = flows of capital; Thin arrows = other dependencies; Natural elements in blue, Human-derived elements in yellow.

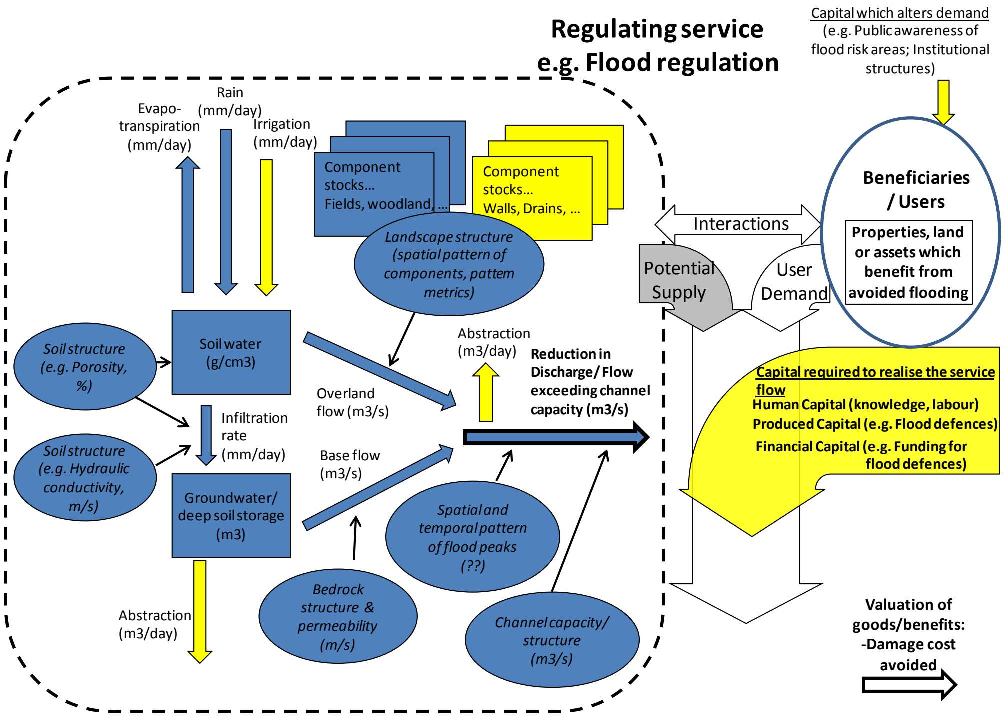

Figure 5. Simplified diagram showing natural and human capital inputs to a regulating service: flood regulation. The potential service is regulation of flooding, the realised service is reduced flood risk for people and infrastructure in the catchment. Key as for Figure 4. Dual blue/yellow shading indicates combination of natural and human elements.

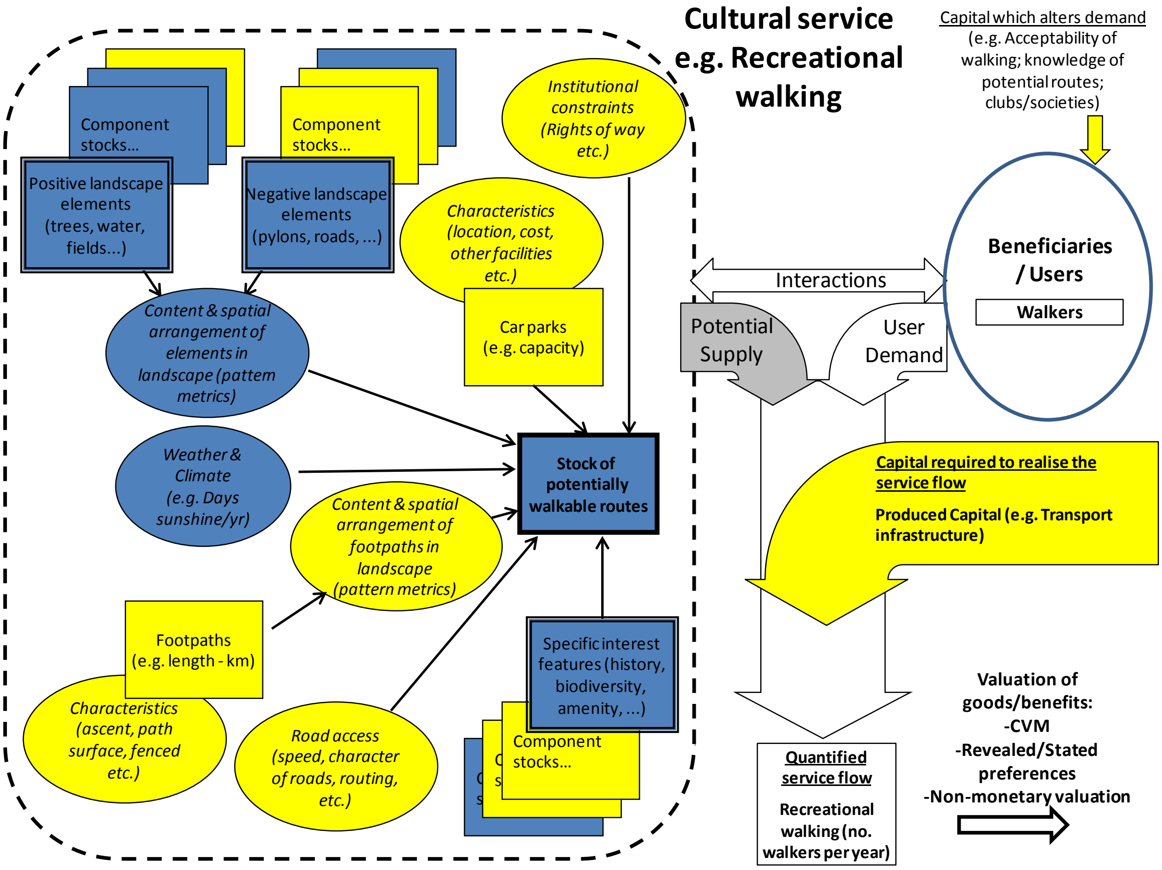

Figure 6. Simplified diagram showing natural and human capital inputs to a cultural service: recreational walking. The potential service is routes available for walking, the realised service is recreational walking by a specified set of beneficiaries. Key as for Figure 4.

4.4.2 Feedbacks & interactions between users and the level of realised ecosystem service

Although we attempt here to make a distinction between human-derived capital required for the potential service to exist, the role of humans as beneficiaries of the service, and the additional capital necessary to realise the service flow, this separation is not always straightforward to achieve. Recent authors have included some components of human-derived capital within ecosystem service capacity. For example, Burkhard et al. (2014) include facilities such as cabins and hotels within ecosystem service stocks, and Remme et al. (2014) acknowledge the difficulties in separating human and natural capital inputs in agro-ecosystems. Villamagna et al. (2014) include social capacity as an element within ecosystem service capacity, but only within cultural services. To add further complexity, for a service to be realised, there are often interactions between the beneficiaries and both the natural and human capital elements that make up the potential service. In particular, the role of the users in shaping the nature and quantity of realised service is most apparent for cultural services. Since cultural services rely to a great extent on human interactions with the landscape, how the service is realised depends on how various categories of beneficiaries perceive it. In the recreational walking example, although natural landscape elements are usually regarded as positive (e.g., water and trees), and human elements as negative (e.g., buildings, electricity pylons, wind turbines) (Research Box/LUC & Minter, R. 2011; Norton et al. 2011), the perception of these features as 'positive' or 'negative' is dependent on the beneficiary and on their social and cultural influences

(Milligan & Bingley, 2007). Many people prefer a human dimension to the landscape, for example the agricultural landscapes of lavender fields in the Provence region in southern France are a major tourist attraction. Similarly, isolation and remoteness of a landscape for recreational walking are seen as a positive feature for some people (for whom isolation = solitude, peacefulness, tranquility) but as a negative feature for others (for whom isolation = remoteness, danger, insecurity) (Suckall et al. 2009). Eliciting community values (geographical communities as well as interest-based communities) is therefore important for measuring the value of landscapes in providing cultural services (e.g., Raymond et al., 2009, Kenter et al, under review).

There is a complex interaction of the beneficiary with the social-ecological system in defining the quantity of realised service. An individual will make personal decisions about where to walk based on a range of variables. For example, their reason for going on the walk (e.g. to walk the dog, or to climb a hill), their physical fitness, their personal associations or memories of the area or walk, cultural views on the desirability of the location. At a population level it is the interaction between the attributes held by a group of beneficiaries and the variables which characterise the potential service at any location which govern the level of realised service (Kenter et al, 2013; Sen et al. 2014).

4.4.3 Flows of capital

We discuss here flows of capital (which are often internal to the processes which underlie the potential service), as distinct from flows of service (Issue 1, see section 3). From a systems perspective, it becomes clear that it is not sufficient merely to identify the stocks of natural or human capital that support a potential ecosystem service, but also the flows which regulate the level of the stocks. For most stocks, the level of the stock at any one time is a function of the previous level and the balance between the rates of input and output flows. In the maize production example, the stock of soil nutrients is depleted by flows to the growing crop, but is replenished by inward flows of nutrients from mineral weathering of bedrock (another stock) and by human inputs of chemical fertiliser or manures. Flows can apply to human-derived capital also, for example, the stock of cultural knowledge about the best way to minimise soil erosion can be increased by farmers talking to each other and by seeking advice on issues such as where best to locate access points to fields. However, there are some flows which derive from stocks without appreciably diminishing the quantity or the quality of the stock, e.g. the number of people looking at and appreciating a patchwork of lavender fields does not diminish the stock of the fields themselves[1]. This inter-dependence of multiple stocks and flows is subtly different from what Schröter et al. (2014a) term 'capacity' which looks only at the last point in the ecological production function, and does not necessarily take account of the stocks and flows earlier in the chain, on which sustainable use depends.

Certain services are dependent on the magnitude of flows of capital rather than the quantity of stock *per se*, particularly the regulating services. For example, flood regulation depends on the flow of water moving down a river system relative to the capacity of the channel to accommodate that flow. In a more complex example, the purification or waste regulation ability of a constructed

[1] Arguably, high visitor densities can reduce the quality of such aesthetic stocks, i.e. they are congestible, but this may only apply to certain classes of users, while the popularity of some aesthetic stocks may actually attract other users.

wetland depends both on the rate of flow of waste into it, which might temporarily exceed the binding capacity of soil exchange sites or rates of plant and microbial uptake, as well as the total capacity to absorb phosphorus (the stock capacity).

4.4.4 Stock properties

There are attributes or characteristics of stocks which we term properties which are not stocks in themselves but determine the quality of the stock and affect its contribution to the ecosystem service. Examples of such properties for natural capital stocks include soil type, angle of slope and slope aspect. These attributes can usually be quantified and can be incorporated in models. Examples of properties of human-derived capital stocks include method of irrigation, or the type of surface of footpaths and their steepness. We can also define attributes of beneficiaries, such as socio-economic group, age-group or level of household income, which affect their interaction with the potential service and thus govern the type and quantity of service they consume (Rounsevell 2010).

4.4.5 Spatial and temporal structure

Spatial structure, i.e. the physical arrangement of stocks in space is a system property which is relevant to the delivery of many services (Syrbe & Walz, 2012). For example, soil can be seen as a composite stock composed of stocks of minerals, organic matter, water and air; however, it is how these stocks are physically arranged that determines soil properties like bulk density, permeability or infiltration rates, which control the level of service delivered. Compacted soils have poor drainage and alter the type and yield of crops that can be grown. A particular soil air volume arranged as well-connected pores allows rapid infiltration of water through the soil, while the same soil air volume arranged in poorly connected pores, may slow infiltration rates by an order of magnitude, with implications for rates of runoff and therefore flooding. At a larger scale, in agricultural landscapes the arrangement of components such as hedgerows or ditches in the landscape or the direction of furrows in ploughed fields affect the rate and quantity of water movement across the land and into streams. The same area of tree shelterbelt can have very different effects on infiltration and on overland flow if it is arranged perpendicular rather than parallel to the slope contours (Carroll et al. 2004) or at the top of a slope compared with the bottom (Jackson et al. 2013). For cultural services, studies have shown that people attach different aesthetic values to landscapes depending on the precise configuration of trees within it, for example, whether they are grouped in one block, or distributed across the landscape (Burgess et al. 2009), and the spatial configuration of a footpath relative to points of interest affects its desirability as a route (Syrbe & Walz 2012; Burkhard et al. 2014; Schröter et al. 2014b).

Temporal structure in the timing of flows is also relevant to the capacity of an ecosystem to deliver services, and has implications for how we quantify these flows. For agricultural production, rainfall needs to occur in the season when a growing crop requires it. The timing of fertiliser or fungicide applications also need to be tailored to the requirements of a growing crop. Flood regulation also illustrates the importance of temporal structure. The timing and frequency, as well as the intensity, of rain are major determinants of whether flooding is likely to occur. An illustration of the interplay between spatial and temporal elements is the relative timing of flood peaks of tributaries in a catchment. If all flood peaks arrive at once in the main channel then flooding is more likely; however, if peaks are separated in time and/or space, the resulting more even flow over time in the main channel means flooding is less likely.

4.4.6 The role of supporting services

Supporting services are also dependent on natural and human-derived capital, and are found within the potential service supply side of the diagram in this conceptual approach. For example, in the maize production example, photosynthesis and nutrient cycling clearly underpin crop growth and are dependent on the same capital elements identified in Figure 4. Supporting services are often the processes and functions which link or transform elements of natural and human-derived capital internally within the ecosystem, and are therefore essential to providing the potential service.

4.4.7 Quality of capital

The amount of service provided by the different forms of capital therefore is a function of the magnitude of stocks of each type of capital, but also their spatial and temporal properties and the interlinkages between them. It is the inter-connected whole which provides the service, and the amount of service can be degraded by impacts on any part of the whole (e.g. through pollution or inappropriate management like overgrazing) (Jones et al. 2014). Conversely this also gives multiple opportunities to manage the sustainability of the capital to provide the service.

4.4.8 A case study example

Because this is a new way of thinking about natural capital, demonstrating these ideas with precise examples is challenging. However, one case study can help illustrate components of the thinking. The Glastir agri-environment scheme in Wales, UK, has been designed to meet a policy framework based on the Ecosystem Approach (see Box 1). The target benefits that the scheme must deliver are centred around ecosystem services (water quality, greenhouse gas emissions, soil quality, cultural services) as well as biodiversity, and the extensive monitoring scheme collects data within a spatial and temporal context (Emmett et al. 2014) on elements which can readily be identified to categories of natural capital and human-derived capital.

In summary, using a consistent framework incorporating stocks, flows and other system properties pertaining to both natural and human-derived capital, we have illustrated that co-production is inherent within three very different ecosystem services, at the stage of defining the potential ecosystem service. We illustrate that it is possible, but not always easy, to separately identify how human-derived stocks and flows contribute to each service, at the stages of potential service, in shaping demand, and as additional capital to realise the ecosystem service flow.

5 Implications for sustainable management of natural and human-derived capital stocks and flows

The systematic approach outlined above helps identify the critical elements which ultimately govern the amount of an ecosystem service that can be provided, and to identify which components of the system to manage such that the delivery of those ecosystem services is sustainable. The goals of sustainable management in this context encompass the following: Use of stocks of natural capital and human-derived capital should not exceed critical levels, and replenishment of stocks should be greater than rate of use if some form of recovery of stock level is required. Flows of natural and human-derived capital should not exceed or fall below critical rates. Management should aim to maintain stocks and flows within 'safe' levels accounting for natural variability caused by external factors, thus incorporating ideas of resilience (Biggs et al. 2012). Schröter et al. (2014a) show how comparison of the difference between ecosystem service flow and capacity goes some way towards measuring the sustainability of ecosystem services. But, this does not address the hidden dependencies on the underlying natural capital and human-derived capital stocks on which they depend. We reiterate that this includes sustainable use of the underlying stocks, not just the final part of the ecological production function frequently defined as 'capacity'.

Land managers and decision makers can manage the amount of realised ecosystem service in a number of ways. They can manage the amount of potential service, and they can manage the level of realised service by considering factors which govern both the demand from the beneficiaries, and the efficiency of use of the potential service by those beneficiaries.

Whether the potential services are defined primarily in terms of stocks (provisioning, cultural) or flows (regulating), their components need to be managed in combination, focusing on the particular stocks, flows or their attributes relevant to each service. For example, in order to increase the stock of available timber for harvest from a plantation, the rate of replenishment can be enhanced by stimulating tree growth through application of fertiliser, planting faster growing tree species, or increasing the area of trees planted (at the expense of other land uses). For regulating services, soil structure and vegetation features in the landscape can be managed in order to slow down or minimise overland flow, thereby both reducing flooding and increasing sediment retention. For cultural services, landscape components which alter the perceived quality of the landscape can be managed, for example via planning regulations to ensure uniform and aesthetic building design within National Parks. The spatial adjacencies can also be managed by designing the routing and the characteristics of footpaths or access routes relative to specific areas to increase or reduce visitor flow as desired. Applicable to all services is that management of stocks should consider the properties and attributes which govern stock quality as well as stock quantity, which also control the capital flows from those stocks.

Addressing the beneficiary side of the relationship, managers have an influence on demand and on efficiency of use. Demand for a service can be increased, for example by advertisements or media articles promoting an area as a desirable walking location. Efficiency of use can be managed e.g. by providing infrastructure to accommodate more visitors in the case of some recreational cultural services. The level of realised service can also be controlled more directly for sustainable management purposes, for example via regulations on the number of boats allowed in the vicinity of whales on whale-watching trips to minimise disturbance to the animals. Another mechanism for controlling the level of realised service is via incentive schemes to encourage sympathetic land management, via agri-environment schemes or payments for ecosystem services (PES) schemes (Engel et al. 2008; Mauerhofer et al. 2013). Many of these schemes show that it is often more efficient, and more desirable from ecological and social perspectives, to manage the natural capital in an appropriate manner, than to substitute human-derived capital.

Central to sustainable management is to identify the flows which are rate-limiting for the service or the stocks with the slowest replenishment rate and where substitution by other forms of capital is not possible or acceptable. These are the critical stocks and the critical flows. Extending the ideas of critical natural capital (Ekins et al. 2003) we suggest there is also critical human-derived capital, e.g. knowledge held by indigenous communities. Once the critical stocks and flows have been identified, the rate of use of those stocks in conjunction with the rates of natural replenishment, or the magnitude of flow should also be quantified, to see if current use levels are sustainable. In some cases, natural capital can at the margin be substituted to a degree by other natural capital or human-derived capital, or the contribution to a potential ecosystem service can be enhanced by addition of other forms of capital. However, the extent to which those stock levels can be replenished or enhanced by other forms of capital should be taken into account, and needs to consider whether those alternative forms of capital are themselves being used sustainably. There is a scale context to this assessment, since resources are not used in isolation. For example, soil phosphorus can be supplemented by mineral fertiliser, but the phosphate required to make that fertiliser must be mined from somewhere else in the world. Calculating the sustainable use of capital should consider the demands of all the services which depend on that capital, not just individual services.

In summary, land managers and policy makers can manage the quantity of realised ecosystem service via the natural and human capital which governs the potential service, and via the capital which governs demand from the beneficiaries and the efficiency with which they use the potential service. Sustainable management requires identification of the critical natural and human-derived capital underpinning service delivery. Calculating the sustainable use of capital should consider the demands of all the services which depend on that capital, and not individual services in isolation.

6 Conclusions

In the context of ever-increasing utilisation of finite resources, this paper seeks to address some of the complexities in ecosystem services thinking and the role of natural and human-derived capital within it. Key contributions of the work presented here are that:

We highlight an often overlooked point among environmental scientists that an ecosystem service is only defined in the context of its beneficiaries. Thus, the quantity of realised ecosystem service depends on the amount of potential ecosystem service, those who use that service and the efficiency with which they use it. The value they attach to it is also relevant but should not be the only criterion applied to decision-making in a sustainability context.

We also show how the human-derived capital, that is an essential component of many ecosystem services alongside natural capital, can be separately identified and quantified. It is important that policy makers and land managers understand their combined role in the human-modified landscapes which now dominate the globe and which provide a large proportion of the ecosystem services we receive, as well as the services provided by the dwindling remnants of natural ecosystems which used to be widespread.

Lastly, using examples we show that a systems approach can be applied to depicting and therefore modelling the social-ecological system that provides realised ecosystem services. This is useful because it a) helps visualise the capital stocks and flows which underpin ecosystem services, b) can guide identification of the critical natural and human-derived capital which are key to sustainable use of the services, and c) if applied in a modelling framework allows prediction of how the quantity of realised ecosystem services might change under different conditions of natural and human-derived capital stocks and flows.

7 Acknowledgements

This work arose from a Valuing Nature Network project, funded by the UK Natural Environment Research Council, with additional funding from UK Department for Environment, Food and Rural Affairs. www.valuing-nature.net

Box 1. Natural capital and human-derived capital within the Glastir agri-environment scheme, Wales, UK.

Overview: The Glastir Monitoring and Evaluation Programme is a targeted monitoring scheme to evaluate the benefits provided by the Glastir agri-environment scheme across the whole of Wales through an ecosystem services (ES) perspective. See Emmett et al. (2014).

Policy context: The Environment (Wales) Bill provides a statutory process to plan and manage Wales' natural resources in a joined up and sustainable way, and the Well-being of Future Generations (Wales) Act places six well-being goals into law, and requires public bodies to apply the sustainable development principles.

Data: The data collection focuses on components of natural capital but includes social and economic components, which are being expanded as the scheme evolves, providing an integrated assessment from an ES perspective. These detailed measures include vegetation, soil, water, pollinators, birds, greenhouse gases (GHG), landscape structure and quality, access, and socio-economics. T<u>emporal</u> (rolling long-term monitoring) and <u>spatial</u> (point to landscape to national) aspects are embedded in the programme.

Selected examples interpreted as stocks and flows: While the monitoring scheme does not explicitly take a stocks and flows approach, or separately identify natural capital (NC) and human-derived capital (HDC), it has considerable potential to do so. Illustrative examples include:

- *GHG emissions* are modelled at farm scale based not just on livestock numbers and field area (NC), but also how livestock are housed and managed (HDC), and inputs of fertilisers and other products (HDC).
- *Landscape character* is summarised in a Visual Quality Index which considers <u>negative</u> aspects from built infrastructure (HDC), <u>positive</u> aspects from topography, woodland and water (NC), valued <u>cultural/historic</u> components such as monuments and buildings (HDC).
- *Visual accessibility* metrics incorporate <u>spatial</u> configuration using 3D landscape viewsheds at 5m resolution, which are a function of topography (NC) and small-scale landscape features (trees, buildings – NC/HDC) which constrain visibility of the landscape. They cover both inward-looking and outward-looking views from each central 1km square to its surrounding 3km square.
- *Public accessibility* is calculated from a complete Public Rights of Way network (HDC) for different classes of user (walker, cyclist, horse-rider, small vehicle, large vehicle).

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