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

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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.

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

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60

61 **1 Introduction**

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

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

88 **2 Current issues**

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

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

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

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

130 improved understanding of how ecosystem services are produced, and the role of humans in that
131 process can help guide sustainable management of these stocks into the future.

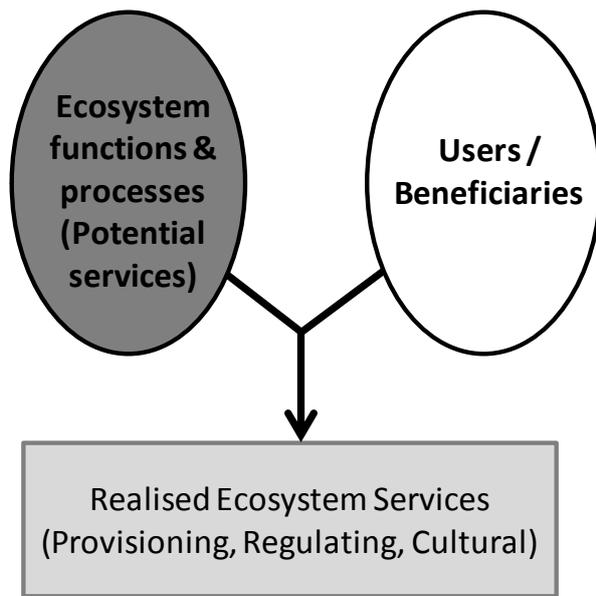
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133 **3 Issue 1. How are ecosystem services delivered: Potential and** 134 **realised services, the role of people as users of ecosystem services**

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

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

157



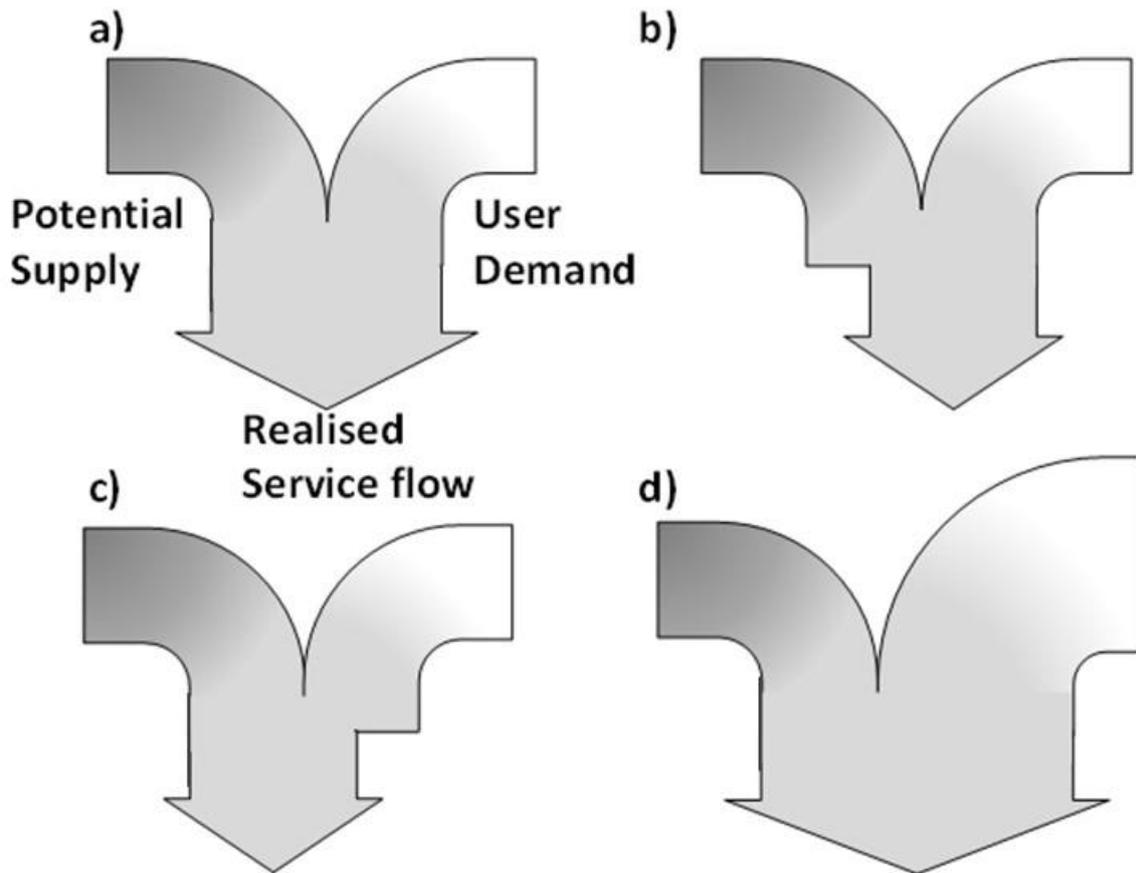
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159 **Figure 1. Potential service supply and beneficiaries are both necessary to define the realised**
 160 **ecosystem service.**

161

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

176



177

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

184

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

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

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- 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.

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

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

218 **4 Issue 2. The role of natural and human-derived capital in the** 219 **delivery of ecosystem services**

220 **4.1 Context**

221 Definitions of ecosystem services initially framed humans purely as users of the benefits provided by
222 the environment. Recent frameworks (e.g. TEEB 2010; 2013; UKNEA 2011) incorporate humans
223 within or interacting with a combined social-ecological system, but without specifying their
224 respective roles. Others (Tallis et al. 2012; Spandenberget al. 2014; Fisher et al. 2013; Burkhard et
225 al. 2014; Remme et al. 2014) go further to highlight both the use of services from the environment,
226 and some interaction between humans and the environment to deliver ecosystem services, although
227 this is often confined to the cultural services. However, the reality is arguably more complex, and
228 there is debate about both the anthropocentric framing of the ecosystem services concept and the
229 role of humans within it (Spash 2009). Increasingly across the globe, landscapes illustrate the
230 connection and inter-dependence between human society and nature, and have been co-produced
231 through a relationship between the two (Gorg 2007, Matthews and Selman 2006). This combined
232 natural and human setting is more accurately described as a social-ecological system (Berkes et al.
233 2002; Olssen et al. 2004; Ostrom and Cox 2010). To a great extent, all three types of final ecosystem
234 service: provisioning, regulating and cultural services are 'co-produced' by the environment and
235 people, even at the stage of potential service supply. This is because, over much of the globe, the
236 landscape is so modified by humans in terms of altered natural processes, agricultural practices and
237 with large-scale infrastructure, that continued human intervention and management of natural
238 capital are necessary for the delivery of many ecosystem services. The challenge from an ecosystem

239 services perspective is to capture this element of co-production. Contrasting with this idea of co-
240 production is the increasing desire to separately identify the elements of natural and human-derived
241 inputs for green accounting or for valuation. We seek to address this challenge by clearly identifying
242 the roles of natural and human-derived capital stocks and flows within a consistent framework,
243 building on the clarified understanding of the elements required for an ecosystem service to occur,
244 outlined previously.

245

246 **4.2 Types of capital**

247 Here we adapt the classification associated with the Sustainable Livelihoods Approach (SLA) (Carney,
248 1998; Solesbury, 2003), which considers five types of capital: natural, human, produced, social and
249 financial. We add a sixth ‘cultural’ capital, and provide some definitions below. We use the term
250 ‘human-derived capital’ to encapsulate produced, human, social, cultural and financial capital, as
251 distinct from natural capital.

252 **Natural capital** has been variously defined as the stock of physical assets in the environment (water,
253 trees, minerals, species, etc.), but also the processes (e.g. water purification, climate regulation)
254 from which we obtain benefits (e.g. NCC 2013). Wider definitions (e.g. Daily et al. 2000), which
255 include whole ecosystems, cause difficulties when trying to understand how the natural components
256 combine with other, human-derived inputs to produce ecosystem services, and fail to recognise how
257 the quality of capital also affects the ecosystem services produced. In this paper we define capital
258 ‘stocks’ as being assets in the environment and capital ‘flows’ as transformations or movement of
259 those stocks. We adopt an encompassing definition of natural capital as “A configuration (over time
260 and space) of natural resources and ecological processes that contributes through its existence
261 and/or in some combination, to human welfare” (Dickie et al. 2014). We discuss below how
262 knowledge of their characteristics and the interactions between natural capital stocks and flows is
263 essential in order to understand not only how services are delivered but how they might be
264 managed sustainably. The distinction between natural and human-derived capital is not clear in the
265 context of domesticated plants and animals. We use the term **cultivated natural capital** (Daly et al.
266 2005) to include crop cultivars and livestock breeds, a term which has also been applied to green
267 infrastructure such as city parks.

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

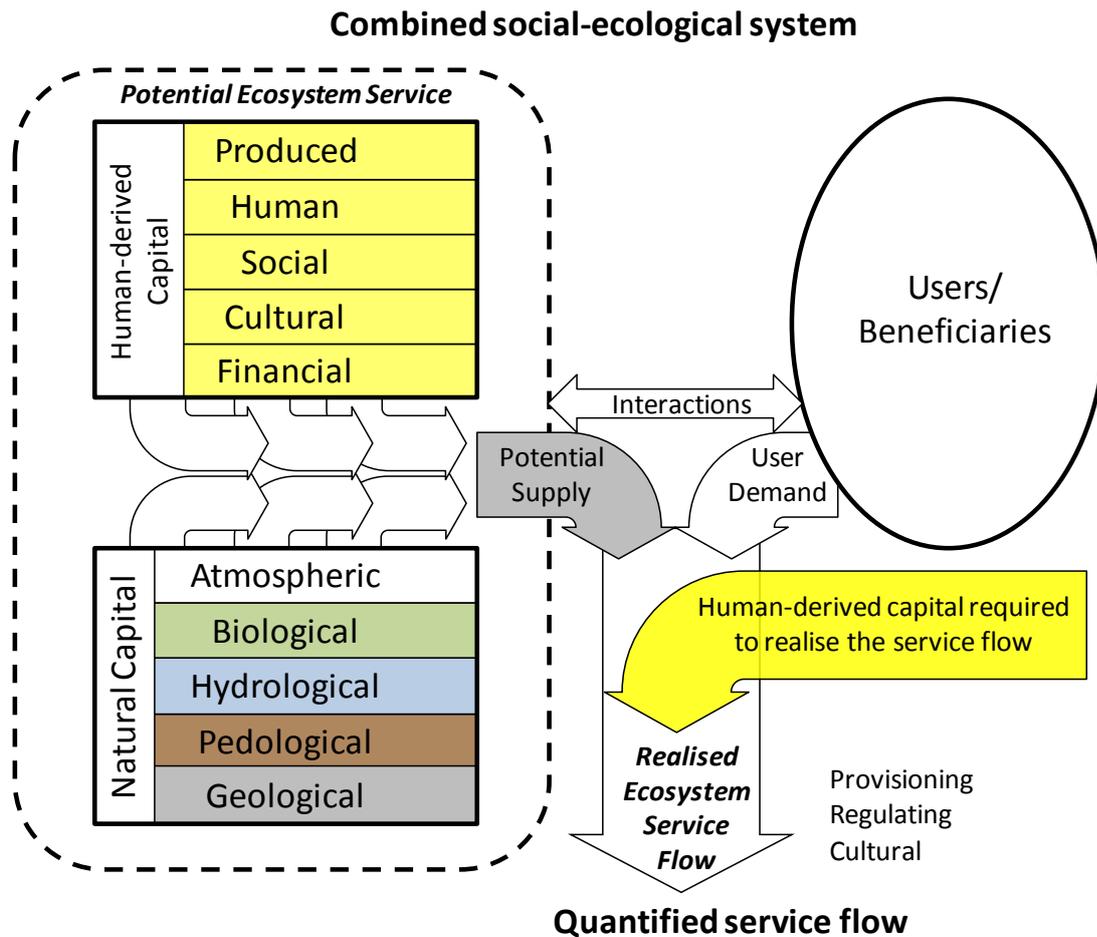
269 **Produced capital**, also called built, manufactured or reproducible capital consists of manufactured
270 assets, such as roads, vehicles, houses, machinery, etc. **Human capital**, defined as the productive
271 capacity of human beings and encompasses the stock of capabilities held by individuals such as
272 knowledge, education, training, skills as well as physical and mental characteristics like behavioural
273 habits and physical and mental health. **Social capital** which refers to the stock of contacts, trust,
274 reciprocity and mutual understanding associated with social networks. It includes both ‘bonding’
275 social capital which consists of accumulated social relationships and bonds of trusts within a tight-
276 knit, closed social group, and ‘bridging’ social capital which consists of relationships of trust in
277 heterogeneous, open groups and between groups (Swendsen & Swendsen, 2009). **Cultural capital**
278 which refers to the broader factors that allow us to interact with each other and the environment,
279 including values and beliefs, socially held knowledge as well as socio-political institutions (Bourdieu,

280 1986; Berkes and Folke 1994; Cochrane, 2006). **Financial capital**, which is money that facilitates the
281 interaction of other forms of capital by funding the activities that might be required for the services
282 to be realised, managed, or improved.

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

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

302



303

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

307

308 **4.3 The building blocks required for a systems approach**

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

318 **Stocks** are a quantifiable amount of material or information, with units for natural capital stocks
 319 often defined in a spatial context. Examples of stocks of natural capital include: soil organic matter
 320 quantified in grams per metre square; volume of water in a reservoir quantified in cubic metres.
 321 Some stocks of human-derived capital can be harder to quantify than others, but examples include:
 322 a social network of people who like to do recreational walking (hiking) quantified in number of

323 individuals and their network connections (social capital); knowledge held by farmers about the
324 fertiliser requirements of different crop varieties (human capital). **Composite stocks** can be
325 measured (e.g. a stock of soil, quantified in tonnes, or centimetres soil thickness) but can also be
326 subdivided and quantified as separate constituent stocks (e.g. for soil: particulate matter, air, water).

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

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

345

346 **4.4 Exploring the issues in the context of examples**

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

352 **4.4.1 Distinguishing natural capital and human-derived capital contributions to the delivery of 353 potential ecosystem services**

354 In all three examples, the essential role of human-derived capital in the creation of potential
355 ecosystem services becomes clear using this approach. For maize production (Figure 4), the
356 elements of natural capital include stocks of soil water and soil nutrients, with input flows of other
357 natural elements of rainfall and solar energy. However, these are augmented by human-derived
358 capital at all stages in the production of a crop. Produced capital is necessary to cultivate the land in
359 the first place in the form of field-drains, or machinery to clear the land, plough, sow and manage
360 the crop. For most crops, stocks of soil nutrients are supplemented by inputs of produced capital in
361 the form of inorganic fertiliser. In some maize-growing areas soil moisture stocks are supplemented
362 by irrigation, which could be defined as a flow of the natural capital of river water or groundwater
363 made possible by the produced capital of the irrigation infrastructure. Other forms of human-
364 derived capital include cultural capital such as the knowledge held by farmers about how to grow a

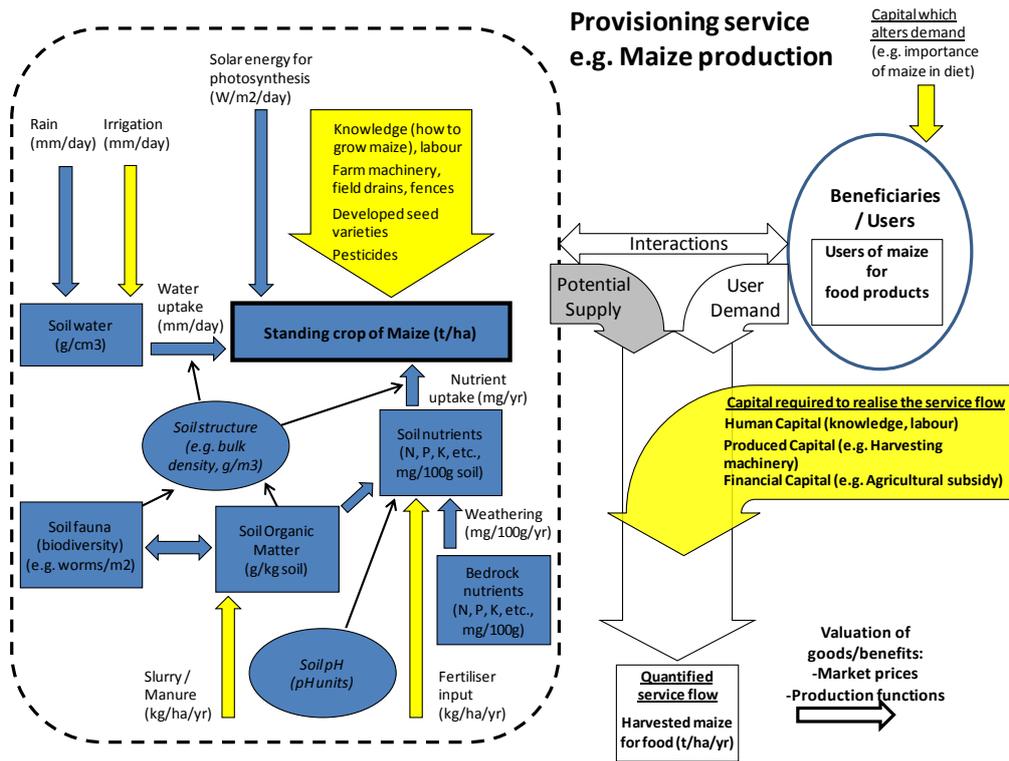
365 crop; social capital such as the sharing of information and co-operation through formal (e.g.
366 extension workers, agribusiness sector workers) and informal (e.g., family, other farmers) networks;
367 and, not least, the developed crop seed varieties sown in the field, which comprise 'cultivated
368 natural capital'. By analogy with standing timber in a forest or plantation, the specified potential
369 service in this case is the production of a standing crop of maize, the realised service is harvested
370 maize for human consumption.

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

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

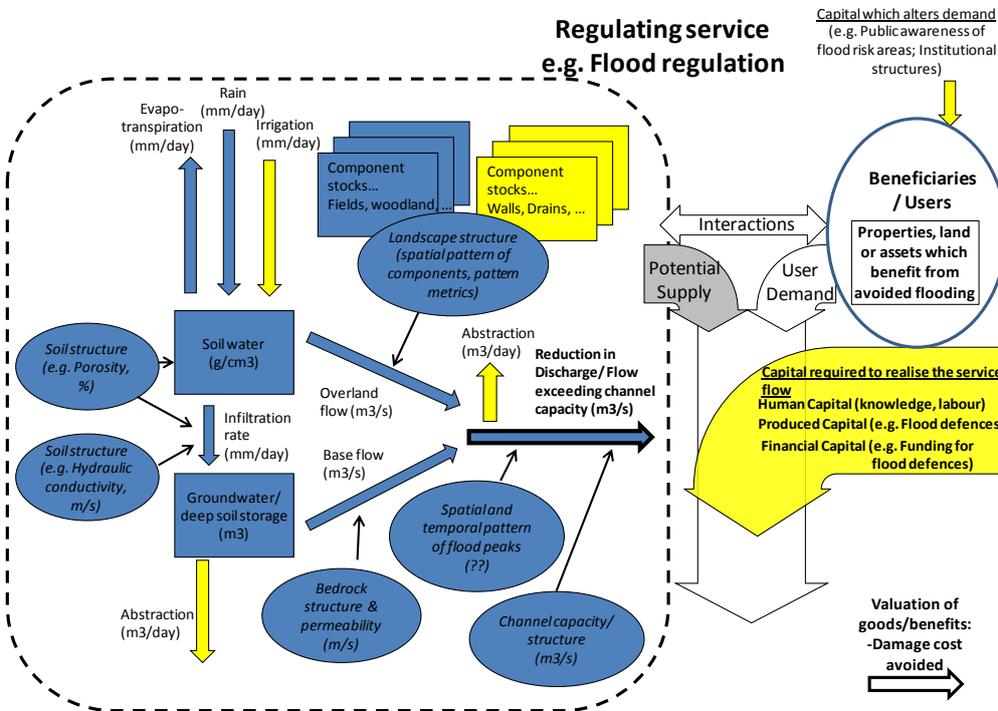
393 The descriptions above have focused on the human-derived capital required for the potential service
394 to exist, but as shown by the yellow arrows to the users/beneficiaries, some human-derived capital
395 plays a role in regulating demand for the service and, as shown by the large yellow arrow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

401



402

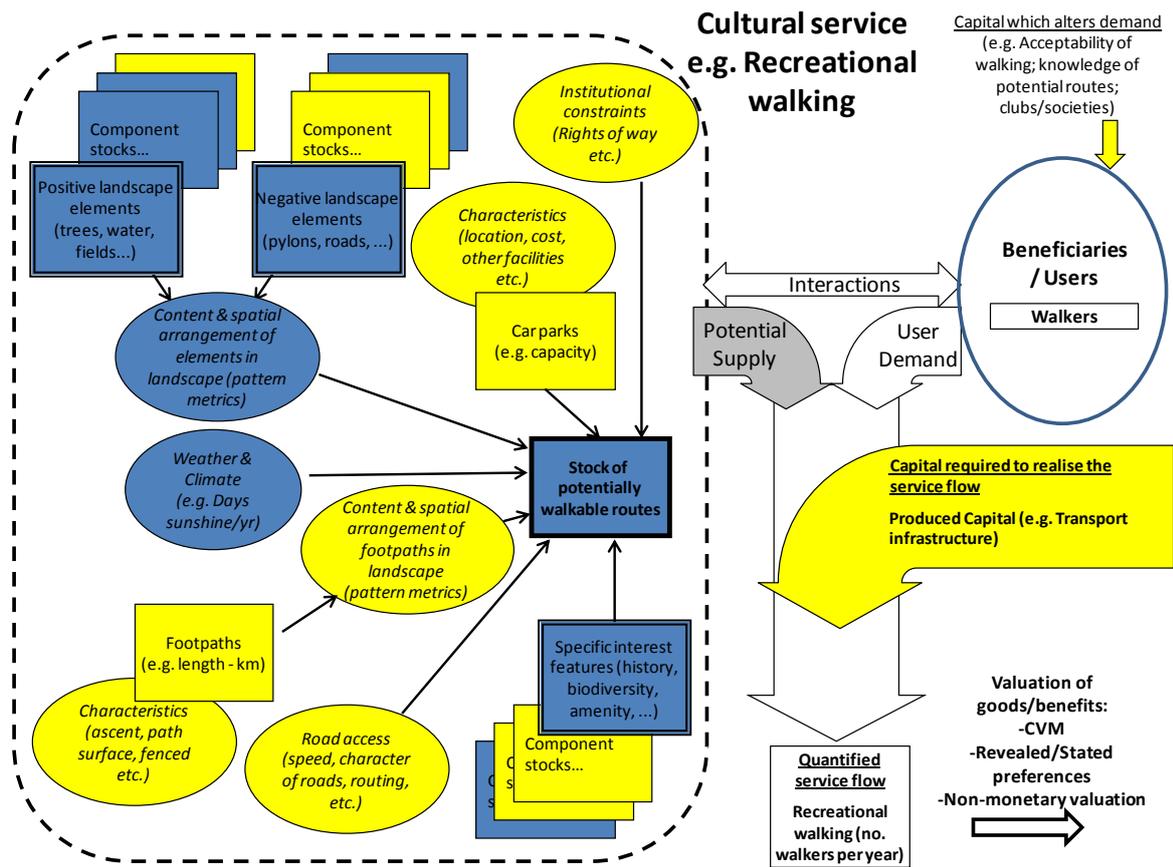
403 **Figure 4. Simplified diagram showing natural and human capital inputs to a provisioning service: maize production. The**
 404 **potential service is production of a standing crop of maize, the realised service is harvested maize for human**
 405 **consumption. Key: Rectangular boxes = stocks, Ovals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



407

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

411



412

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

416

417 4.4.2 Feedbacks & interactions between users and the level of realised ecosystem service

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

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

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

450

451 **4.4.3 Flows of capital**

452 We discuss here flows of capital (which are often internal to the processes which underlie the
453 potential service), as distinct from flows of service (Issue 1, see section 3). From a systems
454 perspective, it becomes clear that it is not sufficient merely to identify the stocks of natural or
455 human capital that support a potential ecosystem service, but also the flows which regulate the level
456 of the stocks. For most stocks, the level of the stock at any one time is a function of the previous
457 level and the balance between the rates of input and output flows. In the maize production example,
458 the stock of soil nutrients is depleted by flows to the growing crop, but is replenished by inward
459 flows of nutrients from mineral weathering of bedrock (another stock) and by human inputs of
460 chemical fertiliser or manures. Flows can apply to human-derived capital also, for example, the stock
461 of cultural knowledge about the best way to minimise soil erosion can be increased by farmers
462 talking to each other and by seeking advice on issues such as where best to locate access points to
463 fields. However, there are some flows which derive from stocks without appreciably diminishing the
464 quantity or the quality of the stock, e.g. the number of people looking at and appreciating a
465 patchwork of lavender fields does not diminish the stock of the fields themselves¹. This inter-
466 dependence of multiple stocks and flows is subtly different from what Schröter et al. (2014a) term
467 'capacity' which looks only at the last point in the ecological production function, and does not
468 necessarily take account of the stocks and flows earlier in the chain, on which sustainable use
469 depends.

470 Certain services are dependent on the magnitude of flows of capital rather than the quantity of
471 stock *per se*, particularly the regulating services. For example, flood regulation depends on the flow
472 of water moving down a river system relative to the capacity of the channel to accommodate that
473 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.

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

477

478 **4.4.4 Stock properties**

479 There are attributes or characteristics of stocks which we term properties which are not stocks in
480 themselves but determine the quality of the stock and affect its contribution to the ecosystem
481 service. Examples of such properties for natural capital stocks include soil type, angle of slope and
482 slope aspect. These attributes can usually be quantified and can be incorporated in models.
483 Examples of properties of human-derived capital stocks include method of irrigation, or the type of
484 surface of footpaths and their steepness. We can also define attributes of beneficiaries, such as
485 socio-economic group, age-group or level of household income, which affect their interaction with
486 the potential service and thus govern the type and quantity of service they consume (Rounsevell
487 2010).

488

489 **4.4.5 Spatial and temporal structure**

490 Spatial structure, i.e. the physical arrangement of stocks in space is a system property which is
491 relevant to the delivery of many services (Syrbe & Walz, 2012). For example, soil can be seen as a
492 composite stock composed of stocks of minerals, organic matter, water and air; however, it is how
493 these stocks are physically arranged that determines soil properties like bulk density, permeability or
494 infiltration rates, which control the level of service delivered. Compacted soils have poor drainage
495 and alter the type and yield of crops that can be grown. A particular soil air volume arranged as well-
496 connected pores allows rapid infiltration of water through the soil, while the same soil air volume
497 arranged in poorly connected pores, may slow infiltration rates by an order of magnitude, with
498 implications for rates of runoff and therefore flooding. At a larger scale, in agricultural landscapes
499 the arrangement of components such as hedgerows or ditches in the landscape or the direction of
500 furrows in ploughed fields affect the rate and quantity of water movement across the land and into
501 streams. The same area of tree shelterbelt can have very different effects on infiltration and on
502 overland flow if it is arranged perpendicular rather than parallel to the slope contours (Carroll et al.
503 2004) or at the top of a slope compared with the bottom (Jackson et al. 2013). For cultural services,
504 studies have shown that people attach different aesthetic values to landscapes depending on the
505 precise configuration of trees within it, for example, whether they are grouped in one block, or
506 distributed across the landscape (Burgess et al. 2009), and the spatial configuration of a footpath
507 relative to points of interest affects its desirability as a route (Syrbe & Walz 2012; Burkhard et al.
508 2014; Schröter et al. 2014b).

509 Temporal structure in the timing of flows is also relevant to the capacity of an ecosystem to deliver
510 services, and has implications for how we quantify these flows. For agricultural production, rainfall
511 needs to occur in the season when a growing crop requires it. The timing of fertiliser or fungicide
512 applications also need to be tailored to the requirements of a growing crop. Flood regulation also
513 illustrates the importance of temporal structure. The timing and frequency, as well as the intensity,
514 of rain are major determinants of whether flooding is likely to occur. An illustration of the interplay
515 between spatial and temporal elements is the relative timing of flood peaks of tributaries in a

516 catchment. If all flood peaks arrive at once in the main channel then flooding is more likely;
517 however, if peaks are separated in time and/or space, the resulting more even flow over time in the
518 main channel means flooding is less likely.

519

520 **4.4.6 The role of supporting services**

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

527

528 **4.4.7 Quality of capital**

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

535

536 **4.4.8 A case study example**

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

545

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

552

53 5 Implications for sustainable management of natural and human- 54 derived capital stocks and flows

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

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

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

88 Addressing the beneficiary side of the relationship, managers have an influence on demand and on
89 efficiency of use. Demand for a service can be increased, for example by advertisements or media
90 articles promoting an area as a desirable walking location. Efficiency of use can be managed e.g. by
91 providing infrastructure to accommodate more visitors in the case of some recreational cultural
92 services. The level of realised service can also be controlled more directly for sustainable
93 management purposes, for example via regulations on the number of boats allowed in the vicinity of
94 whales on whale-watching trips to minimise disturbance to the animals. Another mechanism for

595 controlling the level of realised service is via incentive schemes to encourage sympathetic land
596 management, via agri-environment schemes or payments for ecosystem services (PES) schemes
597 (Engel et al. 2008; Mauerhofer et al. 2013). Many of these schemes show that it is often more
598 efficient, and more desirable from ecological and social perspectives, to manage the natural capital
599 in an appropriate manner, than to substitute human-derived capital.

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

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

623 **6 Conclusions**

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

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

632 We also show how the human-derived capital, that is an essential component of many ecosystem
633 services alongside natural capital, can be separately identified and quantified. It is important that
634 policy makers and land managers understand their combined role in the human-modified landscapes

635 which now dominate the globe and which provide a large proportion of the ecosystem services we
636 receive, as well as the services provided by the dwindling remnants of natural ecosystems which
637 used to be widespread.

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

645

646 **7 Acknowledgements**

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649 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. Temporal (rolling long-term monitoring) and spatial (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 negative aspects from built infrastructure (HDC), positive aspects from topography, woodland and water (NC), valued cultural/historic components such as monuments and buildings (HDC).
- *Visual accessibility* metrics incorporate spatial 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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