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The resource service cascade: A conceptual framework for the integration of ecosystem, energy and material services

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ABSTRACT

Sustainable resource use can be approached from a service perspective, via ecosystem services, energy services or material services. In this paper, we propose an overarching conceptual framework, with which to combine all three service theories and practices. To do this, we review and adapt Potschin and Haines-Young's ecosystem service cascade to create a "resource service cascade" and a classification system. By focusing on a resource's function in society rather than its source, we offer an alternative conceptualisation of the tangible aspects of what an ecosystem and socioeconomic system can provide human populations. We rework various definitions to overcome some of the challenges that emerge when accounting for either natural processes or socioeconomic processes but never both simultaneously. To demonstrate how the resource service cascade works conceptually, we highlight the contributions of resources when used in an illumination system/structure through to visual comfort (the service), need satisfiers and some tangible aspects of wellbeing. Future research, in the form of case studies, is required to operationalise the resource service cascade so that its usefulness can be empirically tested.

1. Introduction

Establishing a more sustainable conception, design and management of human activities is one of the 21st century's greatest challenges (Lewis and Maslin, 2015; Pawlowski, 2011; Steffen et al, 2007, 2015bib_Steffen_et_al_2015bib_Steffen_et_al_2007). Yet, such a framework is essential because the rate of environmental destruction directly linked to resource extraction, use and disposal will continue to grow if resource demand is not curbed (Dittrich et al., 2012; OECD, 2015; Schandl et al., 2016). There is, therefore, an urgent need to better understand the purpose (beyond wealth creation) behind the extraction and transformation of natural resources into the physical structures and processes that support socioeconomic development. One way to do this is through a service perspective.

The service approach is most readily seen through the ecosystem service concept, which provides a theoretical framework to evaluate those benefits (and increasingly the detrimental results) that society obtains from natural processes (Millennium Ecosystem Assessment, 2005; Sukhdev et al., 2010; Vaz et al., 2017). A service perspective has also been employed by researchers who apply ecological economics, industrial ecology and social ecology to problems related to resource efficiency (e.g. Carmona et al., 2021c;

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2021a; Cullen and Allwood, 2010a; Dombi, 2019), resource demand modelling (e.g. Chen et al., 2015; Hunt and Ryan, 2015; Kesicki and Anandarajah, 2011), the link between resource consumption and wellbeing (e.g. Day et al., 2016; Vita et al., 2019) and the development of Energy Service Companies -ESCOs (e.g. Bertoldi et al., 2006; Hannon et al., 2015). In all the aforementioned papers, either an "energy service" or "material service" approach was applied.

For energy services, resource use accounting is restricted to energy flows, such as fossil fuels and renewable sources. These flows support "energy services" such as "thermal comfort" and "physical subsistence" (Cullen and Allwood, 2010b). "Material services" extends the energy service analysis to include non-fuel material flows (e.g. fertilisers, detergents, and lubricants) and in-use material stocks (e.g. buildings, cars and roads). These materials work in tandem with energy flows to support human activity.

There have been various developments within the ecosystem service and energy/material service literature to create terms and categories to better understand the dynamics behind resource provision and distribution in terms of flows, stocks, and services (Carmona et al., 2021b; Haberl et al., 2017; Mace et al., 2012; Vira and Adams, 2009). However, a considerable knowledge gap remains because there has been little, to no, research that connects (or discusses the potential to connect) these three types of services under one overarching conceptual framework. One of the challenges of doing this lies in the fact that "service" and "function", for example, do not carry the same meaning when used to describe an ecosystem, energy or material service (even when one compares two different ecosystem service models).

We propose the resource service cascade as a means to bring together the aforementioned different service conceptualisations under a social metabolism framework. The latter is a systems approach to studying society–nature interactions at different spatio-temporal scales (Haberl et al., 2019). We also develop a unified set of definitions and a classification system to explain how different kinds of energy flows, material flows, and material stocks combine to provide services (and disservices).

The resource service cascade is derived from the ecosystem service cascade (ESC) developed by Potschin and Haines-Young (see Potschin-Young et al., 2018 for the latest rendition). We consider the ESC to be a simple, but effective, means to describe how humans conceive and act out their relationship with ecosystems. It also provides a simplified way of modelling the appraisal/appreciation of the "services" and aspects of wellbeing that ecosystems can provide. The relative ease with which one can communicate the service perspective to end users was a key factor in our adoption of the ESC as the basis for the resource service cascade, even though it may be less accurate than Costanza et al.'s. (2017) dynamic system model.

In many respects, the resource service cascade is an expansion of the ESC. The most significant addition is the explicit inclusion of socioeconomic structures and processes such as road infrastructure and electricity generation. The purpose of the resource service cascade is to illustrate that one can logically follow ecological and socioeconomic processes from natural and humanmade structures through to services and human wellbeing. The aims of this paper are therefore: (1) Review the similarities, differences and the tension points that exist between energy, material and ecosystem services in terms of their definition, scope, and the relationships they have with each other; (2) Using Potschin and Haines-Young's cascade model as a basis, propose an integrated cascade, which can thus be used to incorporate energy, material, and ecosystem services under one conceptual model and one set of definitions; (3) Offer a worked example to demonstrate how the resource cascade operates under a social metabolism framework.

The aforementioned aims are obtained using an anthropocentric lens. This means that the consideration of benefits and services (and by extension detriments or disservices) are restricted to those enjoyed (or suffered) by humankind. It is worth noting, that whilst ecosystem, energy and material services can represent an intermediate step between resource extraction/use and wellbeing, this paper does not venture into the link between resources and the meeting of human needs, which has been done elsewhere (Lamb and Steinberger, 2017; Vita et al., 2019; Whiting et al., 2021).

Indigenous ways of knowing, which lean on eco-centric conceptualisations of Nature do not form part of this paper's scope and thus we assume, for the purpose of the development of the resource cascade, that Nature does not provide "services" or "benefits" per se (unless one accepts Nature's theological benevolence, see Whiting and Konstantakos, 2019). We also do not consider any tangible (or intangible) benefits that can be obtained when one considers the spiritual or sacred value of ecosystems, which are fundamental to alternative ways of knowing about, interacting with, and ultimately conserving the natural world (Misiaszek, 2017, 2020bib_Misiaszek_2017bib_Misiaszek_2020). The benefits associated with mental health improvements and landscape aesthetics (see Engemann et al., 2019, for example), are not addressed either because they are not easily converted into what constitute resource flows and stocks within a social metabolism framework.

2. Literature review

In this section, we explore the concepts and classification of "services" (and "disservices"), as applied in ecosystem service and social metabolism literature. This analysis forms the basis for a set of definitions that describe the interactions that occur between humans and resource flow and stocks, regardless of whether the resources come directly from the ecosystem or via the socioeconomic system.

2.1. *What does the term "service" mean?*

The "ecosystem service" concept acknowledges that ecosystems provide physical flows, stocks and immaterial assets that contribute to aspects of human wellbeing (Costanza et al, 1997, 2017bib_Costanza_et_al_2017bib_Costanza_et_al_1997; Daily, 1997; Fisher et al., 2009; Vaz et al., 2017). The term is typically used to highlight the benefits that humans are said to derive from ecosystems in the form of food, fodder, biofuels, water and air quality, and spiritual and intellectual interactions, amongst other things (Hasan et al., 2020; Holland et al., 2018; Millennium Ecosystem Assessment, 2005). Similarly, "ecosystem disservices" are generally understood as those functions/properties of ecosystems that affect humans in ways that are perceived as harmful, unpleasant or unwanted (Blanco et al., 2019; Campagne et al., 2018; Lyytimäki, 2014; Lyytimäki and Sipilä, 2009; Shackleton et al., 2016). Consequently, examples of disservices include those linked to allergens, pathogens, pests, and other elements, including fires and floods, that have the potential to impinge upon human activity (McLellan and Shackleton, 2019; von Döhren and Haase, 2015). Whether an ecosystem is deemed to provide a "service", "disservice" or neither, is deeply connected to an individual's (or group's) view of the world which is, in turn, influenced by geographical location, level and type of education and other socio-political, socioeconomic, and cultural filters that have shaped their values (Blanco et al., 2020; Braat, 2013; Lazos-Chavero et al., 2016; Rasmussen et al., 2017; Shapiro and Báldi, 2014; Tebboth et al., 2020).

A material service occurs when energy and material flows and material stocks come together in such a way that their interaction with an end user fulfils a defined and desired purpose such as "shelter", "health protection and restoration", "thermal comfort", or any of the other services listed in Appendix 1. Fell (2017, p129)'s review paper discusses the scarcity of appropriate "energy service" definitions and ultimately comes up with the following: *Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states*. This conceptualisation of services is also captured in Whiting et al.'s. (2020, p1) definition of "material services" as *those functions that materials*[1] *contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a material flow or stock is supplied by the market.*

There is, to our knowledge, no explicit mention of material or energy "disservices" in any academic database of journal articles. However, other authors have captured similar concepts that can be used to support the definition of a material or energy disservice. Illich (1974), for example, warns of the economic inequality that can occur when energy consumption, and by extension energy services, exist to predominantly benefit the upper classes and do so at the expense of collective social and environmental harmony. Ekins and Max-Neef (2006), meanwhile, highlight the existence of "inhibiting satisfiers" that lead to the excessive meeting of one human need at the expense of others. For example, the emphasis on individual forms of transport might have provided greater freedom to the car user but it has also locked society into high fossil fuel consumption patterns and increasing atmospheric carbon dioxide concentrations to the detriment of food security and people's subsistence (Ivanova et al., 2018; Jackson et al., 2004).

In order to provide a more analogous comparison to "ecosystem disservices", Illich's and Ekins and Max-Neefs' ideas can be fed into the concept of "energy disservices" and "material disservices" via the aforementioned material service definition proposed by Whiting et al. (2020). In this respect, one could view an energy or material "disservice" as those functions that energy or materials offer but which are detrimental to the obtaining or desired end goals or states, regardless of whether or not a material flow or stock is supplied by the market.

Using the energy/material service "sustenance" as a disservice example, we know that human beings require a certain number of kcals. However, whilst all foods contain kcal, not all food lends itself to a service because some people have food allergies. In their case, ingesting certain foods would be a "disservice" because it would interfere with another material service i.e. "health protection and restoration". On other occasions, certain types of "sustenance" might be seen as repulsive due to cultural factors linked to social norms, religious prohibitions, and ethical choices. Thus, whilst meat might be offered as a means of sustenance, some people would see it as a "disservice" because it is detrimental to their sense of "cultural identity" (which is also a material service, see Appendix 1).

2.2. Service framework categorisation

There have been various attempts within the ecosystem services community to develop frameworks which account for the "services" and, increasingly, the "disservices" that ecosystems provide. Czúcz et al. (2018) and La Notte et al. (2017), for example, provide an in-depth comparison of the ways in which various ecosystem services typologies are used to classify different ecosystem services. While Englund et al. (2017) mapped and integrated different ecosystem services frameworks.

The most widely recognised ecosystem service frameworks are the United Nation's *Millennium Ecosystem Assessment* (MEA) (Millennium Ecosystem Assessment, 2005), the European Environment Agency's *Common International Classification for Ecosystem Services* (CICES) (e.g. Haines-Young and Potschin, 2018; Kasparinskis et al., 2018) and *The Economics of Ecosystems and Biodiversity* (TEEB) (e.g. Kumar, 2010; Müller and Sukhdev, 2018). All these frameworks propose overlapping categories with the operational purpose of covering all potential service types. The material service categories introduced by Carmona et al. (2017) and developed by Whiting et al. (2020), were based on the MEA's conceptual framework. As far as we are aware, no such categories have been established for energy services, which in any case could adopt those used in material services. Where helpful, Table 1 cross-references the categories stated by the aforementioned frameworks, in addition to those proposed by Costanza et al. (2017).

Table 1 indicates that there is shared meaning across category definitions and that, broadly speaking, socioeconomic activity can be captured using ecosystem service terminology. Appendix 2 provides a mapping exercise of ecosystem service categories to the material service framework. The main difference between these frameworks is that "essential services" (i.e. those services which provide a person with the bare minimum required for a the most basic functioning) do not appear in ecosystem services because what enables an ecosystem to maintain the health and condition of its structure, processes and characteristics, are those functions embedded in "supporting services". The latter is a category that Potschin-Young et al. (2017) refer to as "intermediate services", because, unlike "final services", they do not directly provide potential benefits to an end user (Fig. 1a). Thus is, incidentally, also why they are not included in the CICES classification. That is not to say that intermediate services are unimportant. On contrary, they are the linchpin

[1] Materials constitute "biomass", "fossil fuels", "metal ores" and "mineral ores", in line with the definitions provided by Fischer-Kowalski et al. (2011) and Krausmann et al. (2018).

Table 1

A comparison of the categories included in service-based methods used for resource accounting and valuation.

Category	MEA (Millennium Ecosystem Assessment, 2005)	CICES (v5.1) (Haines-Young and Potschin, 2018; Kasparinskis et al., 2018)	TEEB (Kumar, 2010; Müller and Sukhdev, 2018).	Costanza et al. (2017)	Energy/Material Services* (Whiting et al., 2020)
Provisioning	Products obtained from ecosystems (e.g. food and water)	All nutritional, non-nutritional material and energetic outputs from living systems (e.g. food) as well as abiotic outputs (including water).	The material or energy outputs from ecosystems (e.g. food, water, and biofuels).	Ecosystem services that combine with built, human, and social capital to produce food, timber, fibre, or other "provisioning" benefits	All product outputs that are generated from socioeconomic activity via "goods and utility production" and "product maintenance and construction". This includes food (endothermic), technical (exothermic) energy and materials.
Regulating	Regulation of ecosystem service processes (e.g. flood and disease control).	All the ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents (e.g. atmospheric compositions and conditions)	The services that ecosystems provide by acting as regulators (e.g. air quality and climate)	ES which combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control, and climate control.	The specific combination of energy flows, material flows and material stocks that maintain a certain condition or standard (e.g. thermal comfort; space comfort; and environmental protection and restoration).
Cultural	Non-material aspects obtained from ecosystem resulting in spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences.	Characteristics of elements of nature that provide opportunities for people to experience cultural aspects of the human experience (e.g. outdoor interactions in the environment, spiritual interactions with the natural environment)	The opportunities that the natural world offers for recreation and mental and physical health, spirituality, art etc.	ES which combine with built, human, and social capital to produce recreation, aesthetic, scientific, cultural identity, sense of place, or other 'cultural' benefits	Non-material aspects obtained from energy flows, material flows and material stocks (e.g. those linked to identity).
Supporting/Habitat/ Interconnection	**Supporting** - Those services necessary for the production of all other ecosystem services	Only applicable as an **intermediate service**: Those elements and features, which are behind the ecosystem's capacity to deliver services. They enable 'final' ecosystem services i.e. what we actually harvest (e.g. hay, timber) or gain from ecosystem (e.g. flood protection, beautiful landscape etc.)	**Habitat** - The living spaces for plants or animals and maintaining a diversity of plants and animals, are 'supporting services' and the basis of all ecosystems and their services.	**Supporting** - These ecosystem functions (e.g. nutrient recycling or refugia) maintaining the processes and functions necessary for provisioning, regulating, and cultural services	**Interconnection** - Large structures that support the functioning of the socioeconomic system (e.g. shelter and transport)
Essential**	–	–	–	–	Those functions that are required to meet vital needs (e.g. sustenance, health protection and restoration).

Note: * The language has been adapted from the original, so it equally applies to services or disservices; ** Term not in use in ecosystem services and hence why no ecosystem services are included here.

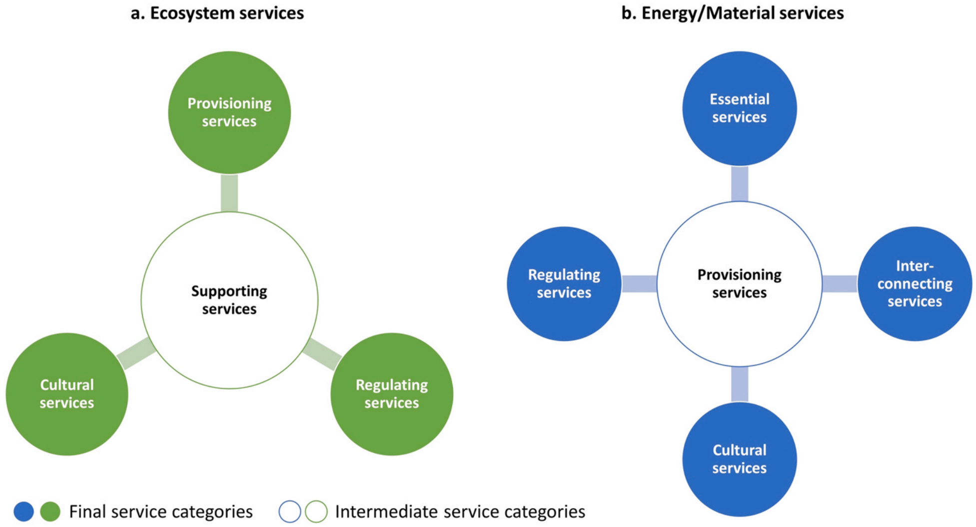

Fig. 1. A comparative schematic for ecosystem and energy/material services.

upon which all the final services are derived.

For energy and material services, "provisioning services" are "intermediate services" because "goods and utility production" and "product maintenance and construction" provide the final services in a socioeconomic system (Fig. 1b). In other words, for both ecosystem and energy/material services the intermediate services provide the means for the system to be sustained. Ecosystem health is predicated on the "supporting" elements and features that enable an ecosystem to function and, conversely, socioeconomic system functioning is predicated on the provision of goods and services, without which there is no socioeconomic system (or at least not one we would recognise as such). In this regard, one can envision the "supporting services" as the purpose of ecosystems (i.e. to continue existing) and "provisioning services" as the underlying objective of the socioeconomic system (i.e. continuation of good production and use, via maintenance).

3. Integrating the ecosystem, energy and material service frameworks

3.1. Analysis of the ecosystem service cascade and derivatives

The ESC is thought to capture how individuals (and society at large) understand Nature's contribution to human wellbeing, via the provisioning and regulation of natural flows and stocks (Potschin and Haines-Young, 2011). Understanding how human interactions are supported by ecosystem services, which, in turn, has a bearing on how they are valued, is important when one considers how, as Bookchin (1996) observes:

Wilderness can be said to exist primarily as a result of a human decision to preserve it. Nearly all the nonhuman life-forms that exist today are, like it or not, to some degree in human custody, and whether they are preserved in their wild lifeways depends largely on human attitudes and behaviour.

As shown by Fig. 2, the ESC begins with the "biophysical structure" as the basis of ecosystem functioning, followed by a "function", which represents the ecosystem's capacity to produce ecosystem "services" (Rugani et al., 2019). A "benefit" signifies the exact way in which an ecosystem service is converted into a socioeconomic product or socioeconomic service with the intent of providing or supporting human wellbeing. Using the example provided by Potschin and Haines-Young (2016): "*A standing crop of trees with particular structural characteristics is the service and the harvested, worked timber is the good or benefit*" where a "*benefit is basically seen as something that can change people's 'well-being', which is understood to be things like people's health and security, or their social relations, or the kinds of choices that can make.*" It is this "benefit" that gives rise to the values, both monetary and non-monetary, that people prescribe to the "ecosystem service" offered by those trees whether that be in the form of timber for shelter, protection against floods, dust, and other types of nuisances, or via the experience of recreational activity. In turn, Potschin and Haines (2016) argue that it is the value that individuals assign to nature that causes them to intensify or alleviate environmental pressure. Hence their feedback loop that goes in the reverse direction to the cascade steps.

From our perspective, this framework is a very helpful conceptualisation of how humans, understand resources and the ways in which resources support them in the undertaking of an activity. However, using the label "benefit" is confusing because various ecosystem service definitions (including that provided by the MEA and Costanza et al., 2017) state that an ecosystem service represents a "benefit" that humans obtain from natural processes and structures. For example, in our opinion, it is difficult to argue that "timber" or a specific type of "tree" is exactly what is being valued here (outside of acknowledging a tree's intrinsic value, beyond what humans think or feel). Instead, surely, it is the way in which that timber is operationalised (e.g. shelter in the form of adequate housing or thermal comfort in the form of an open fire) that creates real (and potential) value? From a material service perspective, timber per se is

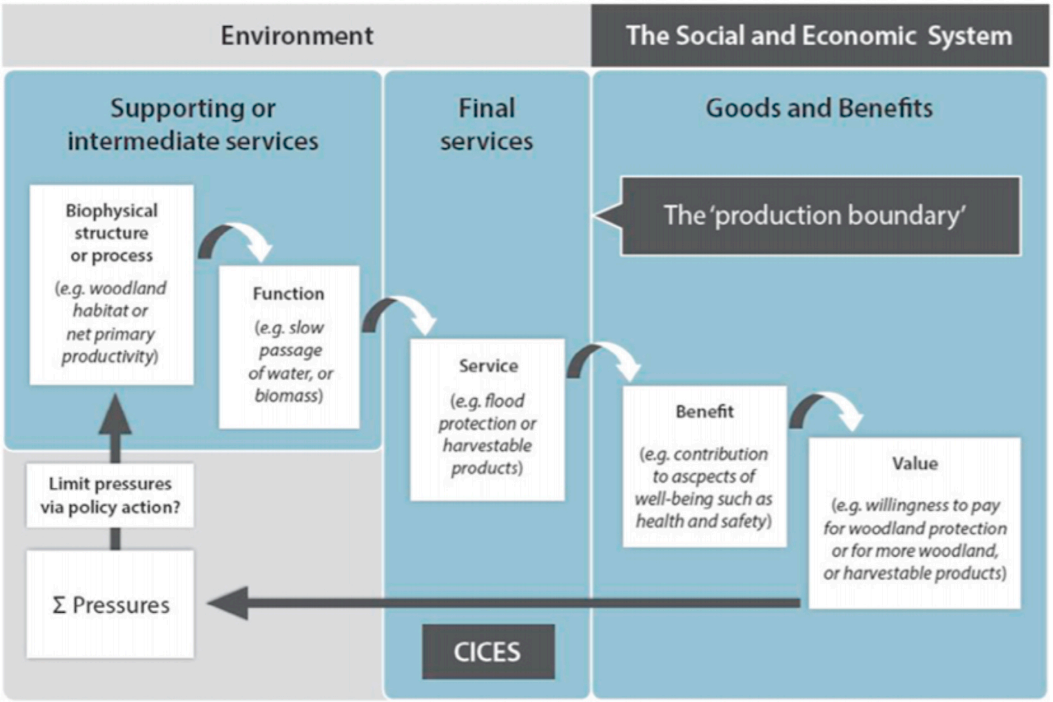

Fig. 2. Ecosystem service cascade. Source (Potschin and Haines-Young, 2017):

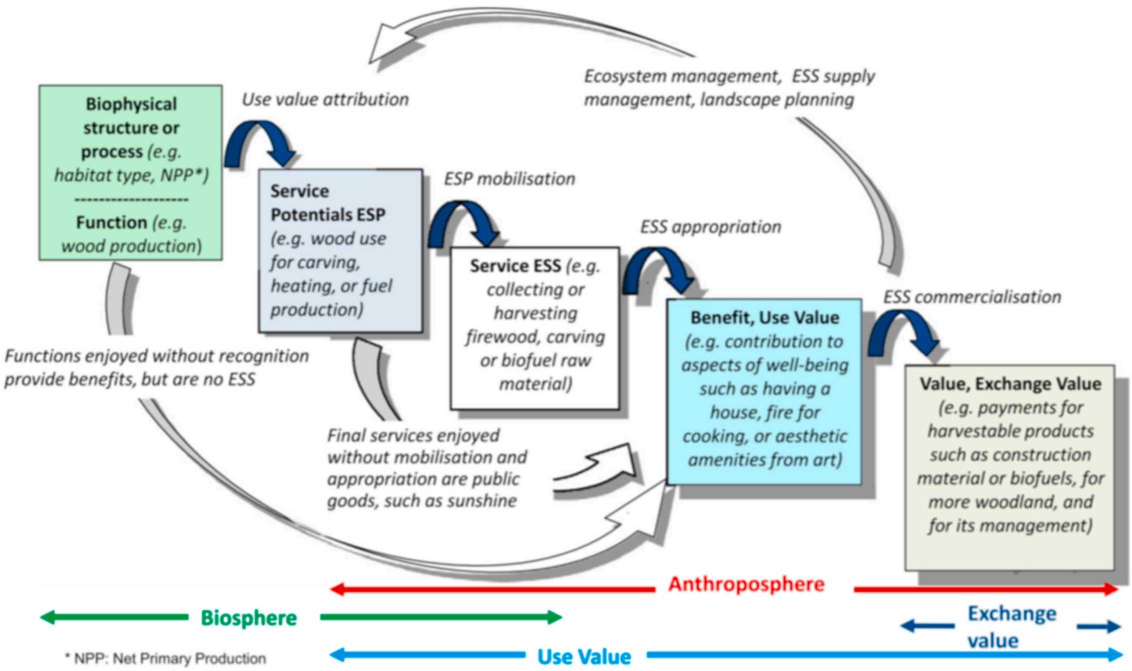

Fig. 3. A modified cascade which integrates ecosystem services with aspects of the socioeconomic system. Source (Spangenberg et al., 2014):

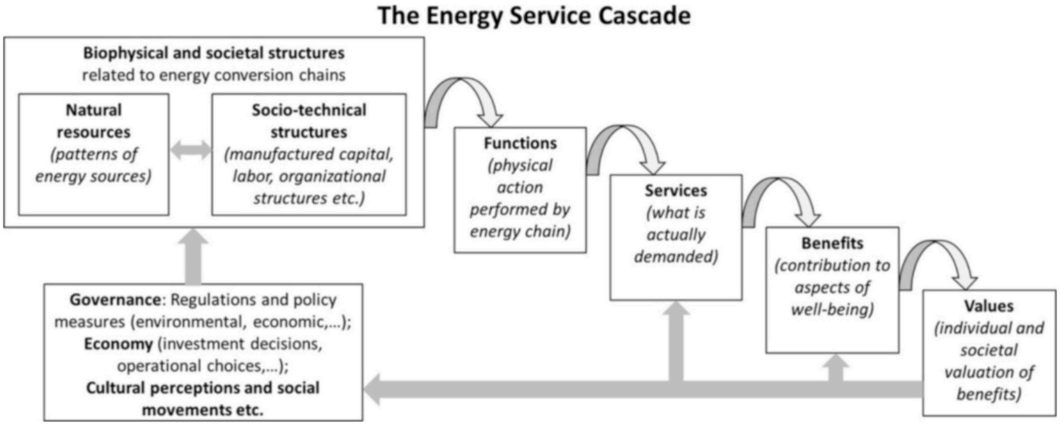

Fig. 4. The "energy service cascade" source (Kalt et al., 2019):

not beneficial but merely a stock or flow. It becomes beneficial following a positive interaction and/or transformation that facilitates certain aspects of wellbeing.

Spangenberg et al.'s. (2014) cascade (Fig. 3) is a development of the ESC, which emphasises the interaction that humankind has with natural processes and how humans subjectively view and value them. Under this framework, an "ecosystem service function" is the provision of an intermediate good that constitutes a fundamental component of an ecosystem service, framed by an understanding that the entire ecosystem service concept and cascade are social constructs and products of spatial-temporal realities.

The second step of Spangenberg et al.'s cascade is "ecosystem service potential", as the natural precondition of ecosystem services. It must be combined with the necessary societal preconditions (e.g. appropriate technology, legal framework or a market for such goods) for the ecosystem service to exist (third step). The fourth step "benefits" occurs when Nature offers a sense of wellbeing directly to an individual (or group) or indirectly following a socioeconomic transformation and transaction. For example, one involving the processing of an ecosystem service into a marketable good or socioeconomic service. For Spangenberg et al. and unlike Potschin and Haines-Young, "benefits" are identified as final goods (e.g. housing or cooking fuel) rather than an intermediate product (e.g. timber), which solves the problem we raised about what exactly constitutes a "benefit".

The cascade concept has also been applied outside of ecosystem services. For example, Kalt et al. (2019) proposed an energy service cascade (EnSC) going from "biophysical and societal structures" to "values", as shown in Fig. 4. The EnSC includes the ecosystem's structure and the entire energy conversion chain. The latter encompasses the manufactured capital and human labour required to generate energy and distribute it to the end consumer. Examples of manufactured capital include power plants, transmission lines and

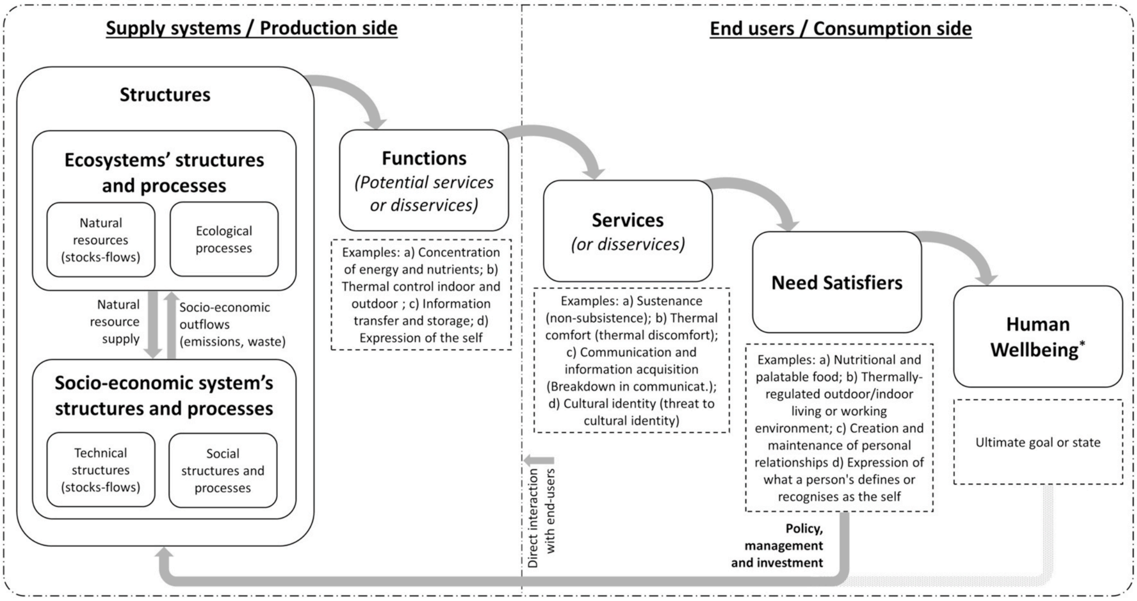

Fig. 5. The resource service cascade. Note: (*) There are various human wellbeing framework one could use, including, theory of human need or capabilities approach. We provide four example chains from function to satisfier in (a), (b), (c) and (d) respectively.

road infrastructure.

The second step in the energy service cascade is "function" which represents a physical action performed by an energy transmission chain. Example functions include vehicle acceleration, heat distribution (thermal regulation) and altering light intensity (via photon emission). Kalt et al. agree with Potschin and Haines-Young's logic that a "function" represents an action that by itself does not constitute a "service" or "benefit". However, their view that a "function" is something that "*humans find useful*" is problematic because "services" and "benefits" form part of the cascade precisely because humans find them "useful". Kalt et al. define "services" as "what humans actually demand" (Fig. 4). However, in our opinion, humans do not demand "services", any more than they demand "functions" or "benefits". There is also a problem with stating that "*humans find it useful that a vehicle is accelerated by a vehicle's internal combustion engine, or that food is kept fresh in a fridge*" because whether someone finds acceleration "useful" depends on the scenario at hand. Vehicle acceleration is far from "useful", if it happens to be one of the causes behind a fatal car accident. The same holds true for refrigerated food. In our opinion, "functions" are not generators of wellbeing or harm per se, but instead offer the prerequisites to a service or disservice.

For Kalt et al., "services" correspond to the "*requisite direct interaction with an end user who can make use of that light intensity or thermal regulation before it becomes illumination or thermal comfort respectively*". They state that "benefits" refer to the potential outcome of an energy service, which for "thermal comfort" is "not freezing in winter" and for "illumination" (which we consider to be a function rather than a service, see Section 4.2) is the ability to participate in social life after sunset. Understanding "benefits" in this way links resource use to the sociological understanding of how materials such as timber, feed into services and contribute to wellbeing through the meeting of human needs.

We can use the aforementioned insights to help us better understand how certain cultural services (e.g. recreation) do not constitute an ecosystem service, but instead the "benefit" that results from multiple services, including what we would refer to as "material services", in addition to "ecosystem services". From a material service perspective, and using "recreation" as an example, a forest parkland frequented by local residents provides "wellbeing" via a specific combination of stocks and flows that constitute the forest (as accounted for under ecosystem services) *and* the landscaped picnic area (as accounted for under material services).

4. Resource service cascade: conceptual framework

4.1. Conceptual basis

For our combined ecosystem, energy, and material services conceptual model, which we name the "resource service cascade", we take Potschin and Haines-Young cascade concept as our starting point. We believe that the ESC captures a simple, but effective, means to describe how humans conceive and act out their relationship with ecosystems. The ESC also represents the way in which humankind tends to appraise/appreciate the "services" ecosystems provide and the way in which they tend to acknowledge their dependency on Nature, when it comes to attaining aspects of wellbeing.

From Kalt et al. we take their more comprehensive understanding of the interrelationship and co-dependencies that exist between the energy chain and natural processes and structures. However, we expand their cascade beyond energy services to incorporate both ecosystem and material services because energy services do not capture all the stocks and flows that are provided by Nature, and which are critical to socioeconomic functioning. Energy services also fail to properly account for the fact that some services, such as "shelter" are predominantly supported by material stock and that the embedded energy of that stock is only one of the multiple aspects that

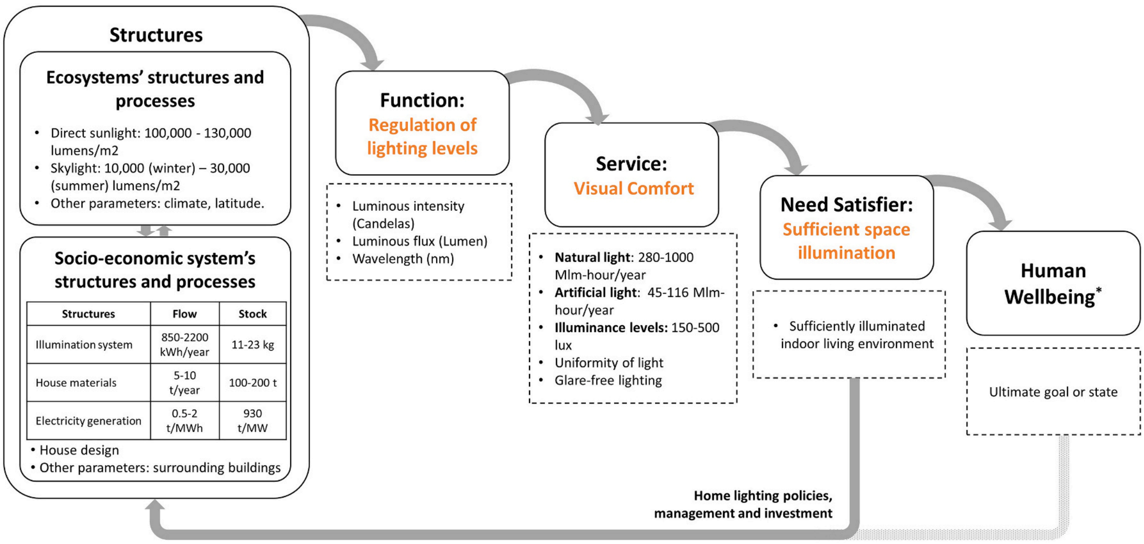

Fig. 6. The resource service cascade applied to visual comfort in a residential building in Northern Europe.

needs to be considered when following the cascade from the ecosystem and socioeconomic systems/structures through to wellbeing.

By identifying a dynamic overlap between ecosystem and material services, Spagenburg et al. gives us a partial blueprint for how we could combine the EnSC and the ESC. From both Kalt et al. and Spagenburg et al. we borrow heavily from their perspective on what constitutes a "benefit", although we label it differently to avoid confusion, given that all steps along the cascade have the potential to be beneficial. For this reason, we opt for Doyal and Gough's (1991) term "need satisfier", a concept which was first introduced by them in their "Theory of Human Needs" (not be confused with Max-Neef's (1991) theory of the same name). Within Doyal and Gough's framework, "need satisfiers" refer to the spatial-temporal specific means and ways that intermediate needs are made manifest in society, so as to adequately ensure the meeting of basic human needs, which they deemed to be "physical health", "autonomy of agency" and "critical participation". In other words, they argue that resources provide the physical structure of an intermediate need. An example of the latter is adequate housing because it is this housing that facilitates a person's ability to maintain health, operate with agency and critically participate in society (e.g. access to voting rights, banking services and employment opportunities). This "need satisfier" definition is not the same as Max-Neef's (1991) "satisfier", which is much more existential and axiological in scope.

The application of Doyal and Gough's needs satisfiers concept to resource consumption is not new. Gough (2017a;2017b) makes the connection between resource consumption, carbon emissions and the need to balance the meeting of intermediate human needs (e.g. adequate housing) with the reduction of consumer demand so that planetary limits are not surpassed to the detriment of meeting basic needs. Likewise, Koch et al. (2017) highlight the usefulness of Doyal and Gough's need satisfiers for the development of a conceptual framework for degrowth. Rao and Min (2018) proposed a "Decent Living Standards" (DLS) threshold in order "to identify what universal material satisfiers are required by people everywhere". Rao and Min (2018) suggest that intermediate human needs are met when there is a minimum floor space of 30 m^2 for a family of three, adequate lighting, and an adequate freshwater supply of 50 L per capita per day and safe waste disposal via in-house improved toilets. When framed in terms of the resource cascade, Rao and Min were proposing sufficient "shelter", "visual comfort", "hygiene" and "environmental protection and restoration" (see Appendix 1).

We also replace "values" with "wellbeing", removing the assumption that what we are looking at economic values and price. All the other labels (e.g. function) are maintained, but their definition is modified to better distinguish between the cascade steps (see Section 4.2). These definitions are embedded in the lexicon and conceptual analysis offered by a material services framework, as opposed to one primarily focused on ecosystem services.

Our cascade uses a service perspective to flatten the distinction between those resources that are traditionally viewed as being provided by the ecosystem and those offered by the socioeconomic system, by focusing on function rather than source. This approach is not the only way in which one can blur this boundary. It could also be overcome with religious or philosophical frameworks (e.g. for example, Algra, 2003; Naess, 1995; Shah-Kazemi, 2019; Whiting and Konstantakos, 2019) but these do not serve our purposes here of creating a cascade for use within social metabolism.

4.2. The resource service cascade and definitions

The resource service cascade has five components that result from various interactions (Fig. 5). The physical basis for all these interactions is the **system** or **structure**. We define the system as *an organised set of interdependent interactions that work together to achieve a defined purpose*. It is constituted by two sub-systems: one that encompasses socioeconomic structures and processes and another which is comprised of ecosystem structures and processes. Example of structures in the resource cascade include "agri-food production and distribution" and "public or private health provision and access". Within the theoretical scope of the resource cascade, the identification of each system establishes the limitation of what a collection of stocks and flows are used for within society. Although, in reality this situation is much more complex and fluid, restricting systems or structures in this way allows for practical accounting mechanisms and calculations.

The next link in the chain are **functions**, which, and we agree with Kalt et al. (2019), correspond to *those actions performed by a system/structure that forms the physical basis of service provision*. In the resource cascade, an example of a "function" is the concentration of energy and nutrients occurring in an apple growing on a tree or being made into an apple pie. This concentration of nutrients leads to "sustenance" as a service, in the form of kcal, for example, regardless of whether those kcal come from the ecosystem directly (apple) or indirectly i.e. combined with socioeconomic processes (apple pie). We define a **service** as *those functions which upon interaction with an end user contribute to personal or societal activity, with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not those functions are supplied by the market.* For "sustenance" to be considered a **needs satisfier** it would have to support *the physical aspects of human wellbeing, which is determined by the spatial-temporal particularities (including geographical location) of that service*. This means that the kcal would have to be constituted in such a way that an end user finds the food appetising due to cultural or personal reasons. Thus, the food in question would still provide "sustenance" but not be regarded as a "needs satisfier" if it did not permit an end user to experience a sense of wellbeing.

The concentration of energy and nutrients (the function) would not provide "sustenance" if they provided empty calories either because it would have a detrimental effect on other services such as "health protection and restoration". In this instance, the kcal would constitute a **disservice**. We define the latter as *an interaction with an end user that results in real or perceived negative impacts on personal or societal activity, which are detrimental to the obtaining or desired end goals or states, regardless of whether or not those functions are supplied by the market.* The inclusion of "supplied by the market" emphasises the fact that one can equally obtain a disservice (or service) from an apple growing on a wild apple tree as much they could from buying a piece of apple pie in a bakery. Appendix 1 offers a comprehensive breakdown of all the service types that feed into the resource service cascade. These services were identified following a comprehensive literature review of those researchers that had proposed their own energy and material service categorises to better explain the relationship between resource use and the provision of the material intermediate steps to societal function, and in some cases, wellbeing. In particular, we borrowed from the work of Nakićenović et al. (1993), Grünbühel et al. (2003), Cullen and Allwood (2010a, 2010b), Knoeri et al. (2016), Fell (2017), and Kalt et al. (2019), who trace energy flows from resource extraction through to energy service; and Baccini and Brunner (2012), Rao and Min (2018) and Whiting et al. (2021, 2020), who link material consumption and accumulation to material services.

4.2.1. Worked example: visual comfort

Visual comfort is obtained when a person experiences an appropriate quality and quantity of light for a given purpose undertaken in a given space at a given time. The range of light levels considered comfortable will depend on various factors, beyond the activity being undertaken, including the duration a person is exposed to a certain level of light, their age, eye colour and personal preferences. It will also depend on the hour of the day, season, latitude, and surrounding environment.

When one considers how the tangible properties of visual comfort (not including aesthetics and psychological aspects because of the challenges of converting them into stocks or flows) may contribute to certain elements of wellbeing, one could imagine a person who enjoys reading, painting or doing a similarly creative activity indoors. Their ability to access lighting, both natural and artificial, will enable then to undertake this activity in the privacy of their own home, where they might feel most safe, comfortable and/or creative. The combination of natural and artificial lighting will also extend their window of opportunity to undertake that activity into the evenings or early mornings, especially in a winter nearer the poles, when natural light levels are insufficient. The needs satisfier, which may lead to wellbeing, is sufficient space illumination for the maintenance of circadian health and the aligning of the circadian rhythm with the natural day-night cycle. Illumination can be provided by a combination of artificial and natural light or either one of them separately, as highlighted by the "structures" step of the resource cascade (Fig. 6). For ecological structures, light is a result of direct sunlight, diffuse skylight and the light reflected from the ground and surrounding elements, such as trees or buildings. A humanmade illumination system includes various stock such as lamps, luminaires (lighting fixtures), cables and lampposts. Flows include fuels and electricity. In addition, the correct functioning of a modern illumination system relies on extensive raw material extraction, manufacturing, transport, building stock and electricity generation.

Whether or not the visual comfort offered by the sun or a modern illumination structure becomes a satisfier will depend on various factors, including the activity that a person wants to undertake. To comfortably read, for example, more lumen-hours or luxes are needed than if one merely wants to be able to navigate their home. Should a person want to sleep then these same number of lumen-hours that were providing visual comfort have now become a disservice and a source of dissatisfaction. It is important to note that the difference between service and disservice may not be a product of the quantity of light but the "warmth" of the light. While white LED light may offer more light per unit of energy consumption than "yellow", it might do so at the expense of visual comfort because of its harsher impact on the eye. In this respect, illumination is also impacting on "health protection and restoration" and thus is a source of visual discomfort, a disservice. The angle of the lamp and the direction of the light rays are also important considerations. Lampposts, for example, are designed to provide a uniform quantity of brightness at the street level. However, when the luminaire is designed poorly or placed at an inadequate angle, there can be a considerable amount of unwanted and unnecessary shadow. This reduces the service efficiency of the street lighting (see for example Kostic and Djokic, 2009; Silva et al., 2010). Alternatively, one can imagine a lamppost illuminating not only the street but the room of a second floor flat because of the angle of the lamp or type of luminaire. In this regard, the luxes provided to the street user would provide visual comfort while causing visual discomfort to the person whose bedroom is artificially illuminated by the lamppost outside.

The tangible elements of visual comfort provided by resource flows and stocks can be measured with regard to illuminance on surface (lux), luminance (candela/m2), light uniformity, unified glare rating (a classification that goes from 5 to 40) and lumen-hours, amongst others. All these forms of light measurement relate to how visual surroundings are perceived by the human eye or experienced by a human for a given period of time. The choice of units would depend on the scale at which one wishes to consider service provision. Lumen-hours, for example, state the range of light levels experienced by the average inhabitant at the city level (see Whiting et al., 2020, for an historic example). Illuminance on a surface, meanwhile, is a unit of measurement that is useful when considering light levels experienced by a particular individual at a specific location in a specific room.

As discussed in Section 4.2, it is a resource flow or stock coupled with an individual's interaction which distinguishes a function from a service. If a light was left on but no one was at home, then the light being emitted by a lamp is simply a function of the illumination system. There are various ways of measuring function, depending on the exact parameters one is analysing. For example, one could consider the luminous flux or lamp efficacy, which are measured in lumens and lumens/Watts respectively. If one is measuring the light emitted from the sun, one could, for example, evaluate the spectral distribution (Watts/nanometre). All measurements of "function" directly relate to the potency and the efficiency of the light source and not parameters such as how far an object is from that source or its angle to it, which are more associated with "service".

Lastly, the cascade can be used to highlight the fact that illumination is not a service per se but a function that may provide visual comfort or visual discomfort as one navigates a room, for example. In fact, illumination can support many resource services including "sustenance", say in a greenhouse, for instance, and cultural services such as the ornamental lighting of monuments, gardens or museums (see Zielinska-Dabkowska et al., 2019). Illumination can also be used to support "health protection and restoration" as occurs when ultraviolet is used to sterilise surgical equipment or for the treatment of certain skin conditions (Kemény et al., 2019). Light can also play a role in the service of "environmental protection and restoration", which is something that is being evaluated when one considers the impact of light pollution on migratory birds (McLaren et al., 2018). In this respect, one can create a cascade that highlights the multiple resource services that rely on lighting functions. This holistic vision of the cascade also helps with the assessment of those interactions and trade-offs that interplay within, and across, the various cascade steps. Picturing services in this way also facilitates assessments of how illumination leads to human satisfaction and certain tangible aspects of wellbeing.

5. Discussion

We proposed a framework with the aim of removing some of the linguistic and operational challenges that are can be found in the resource use literature when social metabolism is approached from a service perspective (energy, material or ecosystem).

The resource service cascade softens the line drawn between "ecosystem services" and "energy/material services" by focusing on the tangible function rather than the source of a particular energy flow, material flow, material stock or service. The importance of considering function when tracing the transition from ecosystem or socioeconomic production to human consumption stems from the fact that, in line with the Brundtland (1987) definition of sustainable development, current generations do not have to safeguard a particular resource. However, they must ensure that future generations have access to and enjoy a given service which, when combined with other ones, leads to at least the same quality of life as the one experienced presently. In other words, current generations must ultimately leave future ones with a healthy natural environment, along with the technological developments, technical capabilities and institutional capacity required to obtain a combination of resource flows and stocks that would lead to an appropriate level of service. In this regard, a form of resource accounting that focuses on the ways in which resources have the potential to provide functions and services can offer insights into how humans interact with, and derive satisfaction and wellbeing from, resources. Such accounting could also give an indication of resource dependency.

The resource service cascade, which we applied to visual comfort, conceptualises, under a social metabolism framework, how one can identify the interactions within and beyond the socioeconomic system. While far from operational, this cascade is a first step to the accounting of some of the tangible benefits or detriments that occur when we use resources (in the way in which we do) to support human activity and provide aspects of wellbeing. It can also be used to highlight where lighting regulations and technical designs do not fully satisfy the need of visual comfort because they are focused on one set of users (people walking in the street) at the expense of others.

Prior to any operationalisation of the resource service cascade, there are many challenges that need to be surmounted. Firstly, conceptual issues remain when it comes to what is meant by "stock" or "flow". In material service accounting, "stocks" constitute those materials that have accumulated over a specified period of time and "flows" correspond to energy or material units moved or transformed within a defined period of time (Haberl et al., 2019; Whiting et al., 2020). The most similar accounting approach within ecosystem services is that proposed by Jones et al. (2016), whereby ecosystem service flows represent the amount of service an ecosystem can potentially provide to a defined beneficiary relative to demand. Within this definition, "flows" refer to the amount of matter or information that is transferred within a *spatiotemporal* context (e.g. rainfall mm/year or information flows from farmer to farmer). "Stocks" are defined as a quantifiable amount of material or information that is solely measurable in *spatially* defined units such as soil organic matter in grams per metre square, reservoir water in cubic metres or knowledge held by a farming community. Given these nuances, the question then becomes, *how best to come up with "flow" and "stock" definitions that are equally meaningful and applicable to all resources captured by the resource service cascade*? The second challenge is how to measure and aggregate resource services (the physical component of need satisfiers). Carmona et al. (2021c) highlights the fact that service units can be proxies, whereby, for example, mobility (a resource service) can be measured via passenger-kilometres. However, as they correctly state, this unit does not capture all relevant aspects of service provision, because as Sorrell and Dimitropoulos (2008) identify all cars (a form of material stock) deliver passenger-kilometres, but can vary widely in terms their speed, acceleration and the comfort, entertainment, and prestige they provide to the consumer. There is also the challenge of interpretation, as a transport service of the highest quality may not be the one that offers the highest number of passenger-kms. Instead, it is more likely to enable a user to travel fewer kilometres, generating fewer emissions and still accomplish their goals (Whiting et al., 2021). The third challenge is how best to approach and define "wellbeing" within the resource service cascade model. There are various wellbeing frameworks one could use, including the capabilities approach (e.g. Nussbaum, 2003, 2000; Sen, 1994, 1985), Human Needs Theory (e.g. Doyal and Gough, 1991; Max-Neef, 1991) or ancient philosophical schools (e.g. Freeling and Preston, 2019; Whiting et al., 2018). Consequently, a thorough examination of human wellbeing approaches must be considered and one selected for the model to be complete. Future research needs to fill in these knowledge gaps with the help of various case studies to demonstrate the usefulness of the resource service cascade, especially for those working on natural resource accounting and valuation.

Declaration of competing interest

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

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Appendix 1. Resource service cascade classification

Table A1
Resource service cascade classification

Categories	Structures (systems)	End-user stocks and flows examples	Function	Service (Disservice)	Service Description	Need atisfier
Essential services	Agri-food production and distribution	Oven, kitchen items, food	Concentration of energy and nutrients	Sustenance (non-subsistence)	Removal of hunger and thirst	Nutritional and palatable food
	Public or private health access	Medicine, surgical and personal protective equipment	Concentration of active ingredients; health or medical intervention;	Health protection and restoration (health deterioration or impairment)	Non-nutritional aspects of reinstating or enhancing wellness/health.	Physical and mental health
Regulating Services	Clean water supply and cleansing elements (e.g. product, devices, equipment) supply chain	End-user water supply elements (pipes, sinks, detergents, washing machine)	Cleansing actions (e.g. washing, drying, sterilising)	Hygiene or cleanliness (unhygienic or uncleanliness)	Maintenance of hygienic standards at the desired temperature.	Clean body and living/working environments
	Illumination systems	Lightbulb, electricity, light switch	Regulation of lighting intensity (brightness)	Visual Comfort (Visual discomfort)	The artificial support of vision in the absence of sufficient natural light.	Sufficiently illuminated outdoor/indoor living or working environment
	Storage spaces (e.g. warehouse, shops, self-storage units) and packaging supply chain	Bottles, protective films or cases along with fridges, freezers, shed, shoe rack	Packaging and Storage	Protection and safekeeping of goods (material damage and loss)	The preservation and protection of material goods.	Well-protected valued items that are safe from foreseeable damage, spoiling or being lost
	Furniture supply chain	Furniture (including frame and upholstery)	Expansion of useable space	Space comfort (space discomfort)	The physical comfort of a person operating in a given space, and which do not provide heat or cooling as a primary function.	Ergonomic and aesthetically pleasing outdoor/ indoor living or working environment
	Heating and ventilation system	Windows panels, boilers, radiators and pipes, air conditioning units	Thermal control indoor and outdoor (alteration of air temperature and surface temperature, relative humidity)	Thermal comfort (thermal discomfort)	Temperature and humidity regulation through space heating or cooling (indoor thermal comfort) or green and blue surfaces, building materials (albedo of buildings and road coating) and urban form (includes orientation of buildings and street canyons to influence air movements) (outdoor thermal comfort)	Thermally regulated outdoor/indoor living or working environment
	Green and blue infrastructure; Solid and liquid waste collection and treatment	Rubbish bins, air filters, catalyst converters, garden equipment	Regulation of anthropogenic impacts on the environment (offsetting negative impacts, enhancing positive impacts)	Environmental protection and restoration (environmental degradation)	The protection, maintenance or regeneration of soil, water, or air quality (indoor and outdoor environments)	Healthy and functional ecosystems

(continued on next page)

Table A1 (*continued*)

Categories	Structures (systems)	End-user stocks and flows examples	Function	Service (Disservice)	Service Description	Need atisfier
Interconnecting services	Telecommunication systems, graph arts and literature	Personal telecommunication devices (e.g. telephone, fax machine, wifi-router) or items (e.g. books, paper, pen)	Information transfer and storage	Communication and information acquisition (Breakdown in communication and information acquisition)	That which allows people to communicate with ourselves or others even when we don't share the same space or time	Healthy and functional expressions of the self for the creation and maintenance of personal relationships and at least a minimum level of societal participation
	Building construction and repair	Houses, schools, government, and religious buildings	Protection and separation from the elements	Shelter (homelessness or inadequate shelter)	The sheltering for people or those animals (e.g. pets) that are not reared for food or clothing	Sufficient protection and separation from the outdoor elements and those areas occupied by other people
	Transport infrastructure	Motorised and non-motorised vehicles, road, rail and port infrastructure (e.g. stations, runways and motorways)	Transfer of people, animals, and goods	Mobility (immobility)	The movement of people, animals, or goods.	The maintenance and enhancement of personal or work relationship and a minimum level of societal participation
Cultural Services	Cultural systems	Religious and national symbols and objects, items that highlight affiliation to a sporting team, family belonging or political cause (e.g. photos, flags and banners, monuments)	Expression of the self	Cultural identity (threat to cultural identity)	The creation, promoting and the maintaining of the integrity of what is culturally significant to you	The expression and maintenance of what a person's defines or recognises as the self
	Cultural systems	Sporting equipment, arts and crafts, gaming devices, musical instruments	Creative expression and entertainment	Entertainment or recreation (boredom or irritation)	The opportunity for entertainment, rest and relaxation	Appropriate form of escapism, alleviation of stress or the generation of pleasant experiences and the development of social relationships
	Defence structures (from human threats)	Weapons, security cameras, fencing	Safeguarding of people, wildlife and material belongings from anti-social activity	Defence from social ills (Vulnerability to social ills)	The physical and emotional integrity of the self or the group	Freedom of physical and mental expression of ideas without fear of harm to the self, the group or that which is considered sacred or important

Appendix 2. Service Categories

The CICES categorisation framework is an integral component of the ESC model, which has been applied to various ecosystem/ biodiversity mapping and valuation exercises, including those linked to European Union policy (e.g. Maes et al., 2012; Potschin-Young et al., 2018). As it stands, there are 3 categories in CICES (subdivided into 36 service types), no categories and 17 types in Costanza and 4 categories and 16 types in material services. Having established that the respective category that represents the "intermediate services" for both ecosystem services and energy/material services are those that enable the existence of the final services, we now consider the extent of which one can map the CICES (v5.1) and Costanza et al. (2017) ecosystem class types onto the material service categories, in order to match material service types (Table A2).

Table A2
Mapping of ecosystem service categories to the material service framework.

Material Service Categories	CICES V5.1 class examples (types)	Costanza et al. (2017) types	Material Service types
Essential	"Animals reared to provide nutrition", "Groundwater for drinking" and "Mineral substances used for nutritional purposes".	"Food production"	"Sustenance" and "Health Protection and Restoration"
Regulating	"Smell reduction", "Pollination" and "Regulation of temperature and humidity, including ventilation and transpiration".	"Gas regulation", "Climate regulation", "Waste treatment", "Erosion control & sediment retention", "Soil formation", "Nutrient cycling",	"Hygiene", "Visual Comfort", "Packaging and Storage", "Space Comfort", "Thermal Comfort" and "Environmental Protection and Restoration"
Interconnection	*Not applicable as a category – however some ecosystem functions allow for the interconnectivity between the system and therefore the exchange of matter and information**.	"Refugia"	"Communication and Information Storage", "Shelter" and "Transport".
Cultural	"Elements of living systems that have symbolic meaning", "Elements of living systems that have sacred or religious meaning", and "Elements of living systems used for entertainment or representation".	"Disturbance (hazards) regulation", "Recreation" and "Cultural"	"Identity", "Leisure" and "Security"
Intermediate services	"Cultivated plants grown for material purposes by in- situ aquaculture", "Ground water used as an energy source", and "wind energy".	"Water supply", "Raw materials", "Genetic resources", "Water regulation", "Pollination", "Biological control",	"Goods and Utility Production" and "Quality Maintenance and "Construction Support".

* The supporting services concept in the Millennium Ecosystem Assessment captures a similar idea to that referred to by "interconnection" in material services in the sense that shelter is a form of habitat. "Communication and information acquisition" and "Mobility" can be considered socioeconomic equivalents to those ecosystem functions which allow for the transmissions of nutrients and information.

Table A2 demonstrates that certain CICES class descriptors make the classification of the ecosystem service under a material service category and a corresponding material service type relatively easy. "Animals reared *to provide nutrition*", for example, falls under the "essential" material service category and under the "sustenance" material service type. However, other descriptors do not facilitate such mapping. For instance, one is unable to allocate "Cultivated plants grown for energy purposes by in-situ aquaculture" to a final service, as energy production is not a service an end user desires but instead the means by which other services come into existence. For example, one could use the energy contained within biofuel to provide "thermal comfort", "mobility" or "sustenance". Thus, under the material service framework, one categorises this ecosystem service as an "intermediate service", assigning it to the (provisioning) category "goods and utilities". Constanza et al.'s (2017) categories can be mapped onto the material service framework in the same way once the purpose is known. As with the CICES categories, if the purpose is not known then "raw material" and "genetic resources" would fall under the intermediate material service "provisioning".

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