Environmental Development 40 (2021) 100654

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Economic valuation of Earth's critical zone: Framework, theory and methods

Wan Nie[a], Hongyan Guo[b], Steven A. Banwart[a,c,*]

[a] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[b] State Key Laboratory of Pollution Control and Resource Reuse, School of Environment, Nanjing University, Nanjing, 210046, China
[c] Global Food and Environment Institute, University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Keywords:
Earth system
Climate change
Critical zone services
Economic value
Stocks and flows

ABSTRACT

The economic valuation of ecosystem services derived from Earth's critical zone has primarily concentrated on vegetation and surface waters or on a few selected aboveground services; however, the economic value of ecosystem services provided by the atmosphere and shallow lithosphere has not yet been considered substantially. In order to address this research gap, we propose a more explicit and rigorous definition of critical zone services as the human benefits provided by Earth's critical zone. This concept brings a more complete inventory of stocks and flows upon which critical zone valuation methods are based. By considering the 5 interconnected components (atmosphere, vegetation, soil, surface water, groundwater) of Earth's critical zone, we identify from literature review a wide range of critical zone services and classify them into three categories (provisioning, regulating and cultural) defined in the Common International Classification of Ecosystem Services. We do not consider supporting services, whose influence is intrinsic to the values of the other classes, specifically to avoid double accounting. Based on the defined critical zone services, we present a methodology enabling economic valuation of Earth's critical zone that is consistent with partial equilibrium theory and accounts for biophysical and economic input to the analysis. This approach achieves two significant aims that 1) incorporate recent new natural sciences concepts and knowledge in evaluating the structure and function of the critical zone into methods of applied economics and 2) provide natural environmental scientists with access to simplified theory and practice of applied economics that is relevant to valuation methods at the location-specific physical scale of the critical zone. The proposed methodology can be used as a quantitative management tool for economists and policy makers to more transparently enumerate the provision of services arising from the biophysical functioning of the whole of Earth's critical zone in the face of increased pressures of increased population, land use intensification, and climate change.

1. Introduction

Earth's critical zone was first proposed by natural scientists in 2001 as a concept that integrates the structure and interconnected dynamics of the atmosphere, the vegetation, soils, water, and underlying regolith to the depth of weathering fronts within the bedrock (National Research Council, 2001). The critical zone defines an open biophysical system that receives, transforms and transmits inputs

* Corresponding author. School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
E-mail address: S.A.Banwart@leeds.ac.uk (S.A. Banwart).

https://doi.org/10.1016/j.envdev.2021.100654
Received 21 October 2020; Received in revised form 8 July 2021; Accepted 19 July 2021
Available online 10 August 2021

of energy, material and genetic information (Banwart et al., 2019) (Fig. 1) and provides humans with most of their life sustaining resources (Jordan et al., 2001). The term critical is relatively new as applied to this thin planetary surface layer, referring to 1) a critical interface between lithosphere, atmosphere and biosphere of the Earth system, 2) its critical role as the zone of human terrestrial habitation and 3) its fragility under critical pressure from human resource demand. This framing of the critical zone represents a disciplinary merging of concepts from geological sciences and ecological sciences and has more recently interfaced with social sciences as representing human-Earth interactions at the experiential scale of human habitation (Latour 2014, 2018). This study aims to introduce these recent developments from natural sciences into conceptual, theoretical and analytical frameworks of applied economics. We propose this development as an advancement in understanding and delineating the boundaries of the biophysical system,

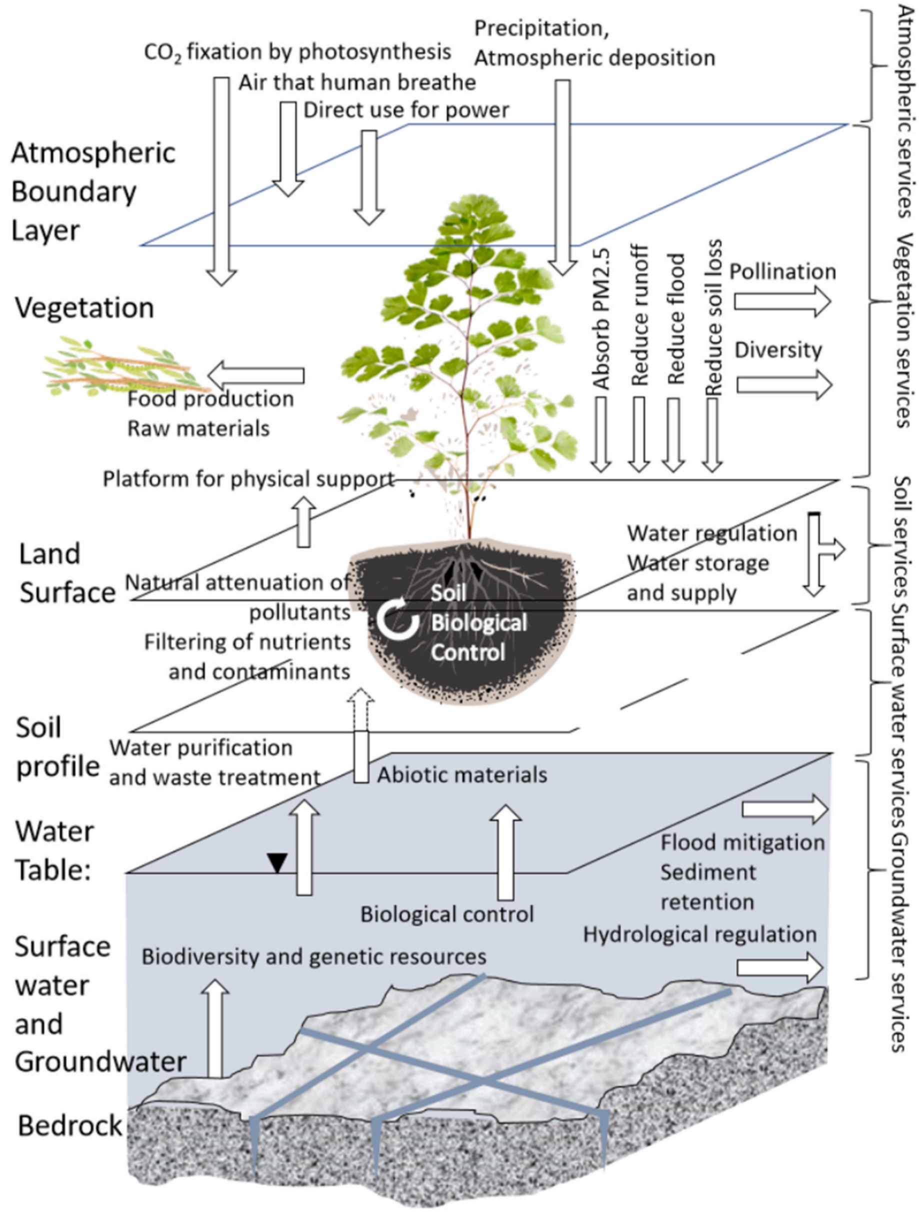

Fig. 1. The conceptual representation of Earth's critical zone and proposed critical zone services as a generalized Earth surface representation of ecosystem and ecosystem services, respectively. Earth's critical zone extends from the top of unweathered bedrock to the top of the vegetation canopy and exhibits dominant material and energy fluxes governed by land-atmosphere, soil-vegetation, shallow geosphere-lithosphere, and land-ocean interactions. Earth's critical zone and initial ecosystem are congruent concepts. However, the ecosystem concept has been historically often subdivided into above- and below-ground components. Previous conceptualizations of ecosystems have often focused primarily on vegetation, soil and surface water. However, near-surface and above-ground processes depend on and are constrained by their interaction with subsurface critical zone processes. Critical zone services derived from the entire interconnected extent of Earth's critical zone, therefore, aid in defining the generalized inventory of stocks and flows that contribute to human wellbeing. Fig. 1 is adapted with permission from Banwart et al. (2019).

and the bounded stocks and flows, upon which ecosystem valuation methods are based. We further aim through this study to enable subject experts in critical zone science and in applied economics to more readily access concepts and analysis frameworks between disciplines.

Tansley (1935) first used the term ecosystem and defined it as "one physical system" that integrated the biotic-abiotic complex of rock, water, air and organisms. Richter and Billings (2015) demonstrated that the critical zone concept is congruent with Tansley's original definition of an ecosystem (Tansley 1935). However, Tansley's original concept became historically substantially subdivided into above- and below-ground environments (Richter and Billings 2015) (Fig. 1) and as a consequence, much of the research on ecosystem services has been focused more heavily on surface processes. However, the functioning of Earth surface biophysical systems substantially depends on and is constrained by interaction with subsurface critical zone processes that are often not included in existing frameworks for ecosystem services valuation (Field et al., 2015). Therefore, a more comprehensive valuation of ecosystem services could be derived from considering the full extent of Earth's critical zone that links above-ground processes and below-ground critical zone processes (Field et al., 2015; Banwart et al., 2019; Nie et al., 2020). This study fills this research gap by demonstrating a methodology enabling economic valuation of Earth's critical zone that is consistent with partial equilibrium theory, considers a more comprehensive structure of Earth's critical zone and can be applied at the location-specific physical scale of habitation for an individual human, household or local community.

The term "environmental services" was coined in 1970 by researchers who were concerned with the decline of ecosystem functions in delivering services to humanity (Gagnon 1973). This approach was further developed by framing ecosystem services as a pedagogical concept designed to raise public interest for biodiversity conservation (Ehrlich and Ehrlich 1981). The milestone article published by Costanza (1997) on the value of the world's ecosystem services and natural capital defines ecosystem services as the flows of benefits to humans from ecological systems and the natural capital stocks that produce them. This concept has been widely accepted as a definition of ecosystem services (Zhong et al., 2020). As modern day societies and economies are becoming increasingly vulnerable to the widespread decline of the stocks and flows of essential ecosystem goods and services (Institute 2000; MEa 2005b; De Groot et al., 2012), environmental scientists and economists addressed the need to develop the concept of ecosystem services through linking biophysical processes to human well-being (Costanza et al., 1997; MEa 2005b; Sukhdev et al., 2010; Sannigrahi et al., 2020). As an example of global risks resulting from human pressures, the UNDP (United Nations Development Programme) projects that the impacts of climate change (including sea level rise, droughts, heat waves, floods and rainfall variation) will add 600 million people worldwide to the number already facing malnutrition, and will increase the numbers facing water scarcity by 1.8 billion by the year 2080 (Kabubo-Mariara and Mulwa 2019). In line with the extension of ecosystem services concepts and development of critical zone science, we propose a more explicit and rigorous definition of critical zone services as the human benefits provided by the stocks within the entirety of Earth's critical zone and the processes and interactions with people that deliver flows of benefits to humans.

There are five advantages of our proposed definition. First, from the fundamental definition of critical zone, it is the constrained terrestrial component of the Earth planetary system that dominantly supplies life-sustaining resources (i.e. benefits) to humans. Second, the critical zone defines explicitly the physical boundaries of the volume and mass of terrestrial stocks that receive, transform and transmit the flows of material, energy and genetic information, which are of benefit to humans. Third, critical zone services are determined by the interconnected whole of the dynamic, interacting physical system, which is a construct of rock, fluids and organisms including people that aligns with Tansley's original concept of an ecosystem. Fourth, the recognition of the reliance of benefits on the interconnected, interacting processes of the critical zone makes explicit the link to sustainable economic development. This conceptual link occurs because sustaining the benefits to humans over time relies on the ongoing flows and transformations (e.g. of mass and energy) that occur from the continuous functioning of the critical zone as a whole. Fifth, the concept of critical zone services provides a conceptual framework to translate and communicate basic research advances in critical zone science into societal benefits for human well-being (Brantley et al., 2006; Banwart 2011; Field et al., 2015). This becomes particularly important as new research efforts to study Earth's critical zone gain insight into the mechanistic linkages between the above-ground and below-ground biophysical processes, and the extent to which the human is vitally dependent on these interactions in the face of increased population, land use intensification, and climate change (Banwart et al., 2019). Critical zone services are, therefore, the defined set of ecosystem services that arise from this specific physical system.

There have been many studies in the past few decades aimed at estimating the economic value of a wide variety of ecosystem services (Costanza et al., 2014; Martin et al., 2020). However, to date, economic valuation of Earth's critical zone is primarily concentrated on selected, largely aboveground, services (Maes et al., 2016; Reynaud and Lanzanova 2017). The economic value of ecosystem services provided by Earth's critical zone including the near-surface atmosphere boundary layer and groundwater has not yet been considered in detail until recently (Richardson et al., 2017; Nie et al., 2020). To address this gap, our study here introduces critical zone services concepts into economic valuation methods aimed at understanding the comprehensive benefits derived from Earth's critical zone. This message is important for decision-makers to better predict anticipated delivery of the full range of critical zone services and how these may be impacted by human activity.

In preparing this study, the following contributions were made: (i) demonstrating the theoretical basis for estimating the economic value of Earth's critical zone; (ii) identifying by literature review the goods and services that to date are associated with Earth's critical zone; and (iii) defining from theoretical principles a transparent and practical methodology that accounts for biophysical and economic feedbacks for location-specific economic valuation of Earth's critical zone.

2. Study methods

On the basis of the 5 interconnected components (atmosphere, vegetation, soil, surface water, groundwater) of Earth's critical zone, we identified from literature review a wide range of critical zone services for each compartment. Based on the identified critical zone services, we suggested a potential economic theoretical basis to describe the economic factors of value creation and from this translated quantitative methods for economic valuation of Earth's critical zone. Then we provided a compilation of biophysical indicators and economic valuation techniques for assessing individual critical zone services.

To identify the critical zone services and their biophysical indicators and economic valuation techniques, we conducted a broad search for published academic papers through online databases (Web of Science and Google Scholar) using the conceptual framework (see Fig. 2) as the basis. Ecosystem services were used as a search term to directly capture the examined critical zone services. Search results were first screened by title and then by abstract for relevance. The most relevant papers were downloaded and read in detail to extract the information required for this study. We only included papers published in English language (see Supplement 1 for the literature included in this study).

We organize the theoretical and methodological development through a series of 6 steps: (1) a conceptual framework (Fig. 2); (2) specifying critical zone processes, structure and functions and anthropogenic drivers; (3) identifying critical zone services; (4) reviewing the economic theoretical basis of monetary valuation of Earth's critical zone; (5) selecting parameters for biophysical assessment of unit stocks and flows of critical zone services; (6) applying economic valuation techniques to monetizing unit value of critical zone services.

3. Theoretical and methodological development

3.1. Stocks and flows of critical zone services

Stocks refer to the capacity of natural capital such as mass, energy and genetic information contained within Earth's critical zone that deliver critical zone services to humans (Rawlins et al., 2018; Vallecillo et al., 2019). Stocks are based on the defined volume of Earth's critical zone and the mass of rock, water, air and organisms contained within. Through solar, meteorological, orogenic and geothermal inputs, stocks support internal biogeochemical cycling that transforms and transmits inputs and produces output flows of material, energy and genetic information in the form of critical zone services to humans. Earth's critical zone comprises five biophysical components (atmosphere, vegetation, soil, surface water and groundwater) that contribute the stocks of natural capital and produce the full inventory of critical zone services to humans. Flows into and out of the critical zone can build or deplete stocks, where the resulting impact of changes in stocks on internal biogeochemical cycling can change the balance of output flows. For example, depletion of soil organic matter due to accelerated loss through physical soil erosion, may reduce soil fertility and the rate of biomass production from vegetation growth. Earth's critical zone is considered degraded where human pressures have caused altered structure and functions that, as a result, are not capable to produce the same range and magnitude of flows of critical zone services to humans (Xiang et al., 2020). For example, mass transport and transformations within an undegraded critical zone supply clean air, substantial biomass and fresh water to humans, while a degraded Earth's critical zone (e.g. soil degradation) is incapable to deliver the full inventory and scale of these services to humans.

Flows reflect the actual use of benefits arising from the natural capital such as mass, energy and biodiversity provided within the Earth's critical zone (del Río-Mena et al., 2020). It is straightforward to recognize the actual use of the majority of provisioning services

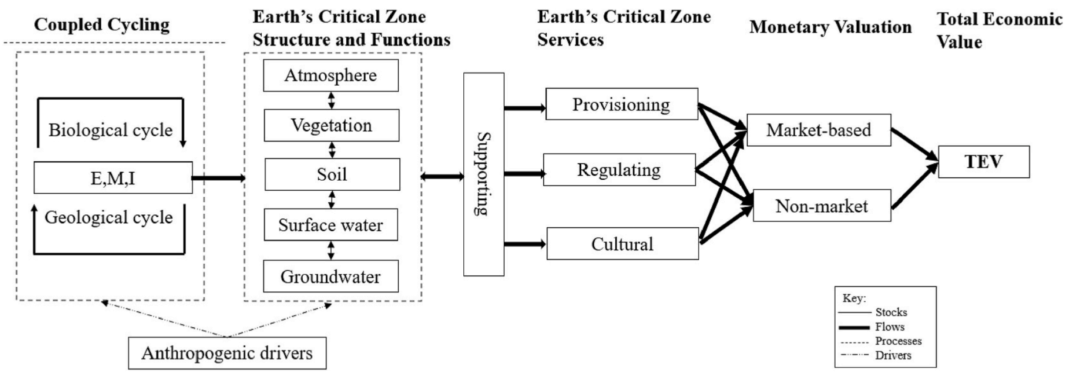

Fig. 2. Proposed framework for economic valuation of Earth's critical zone. Both coupled geological and biological cycles – including conservation of energy (E) and mass (M) as physical and chemical state variables and genetic information (I) as a biological state variable – as well as human activities as anthropogenic drivers, work to influence Earth's critical zone processes and functions. The hydrological cycle, along with other coupled cycling such as biogeochemical cycling is included in Fig. 1. The structure is the volumetric distribution of rock, water, gases and organisms that delineate recognizable physical components (atmosphere, vegetation, soil, surface water and groundwater) and their mass transport that define an open system of Earth's critical zone. Critical zone functions (e.g. water storage and transmission, C and N sequestration from the atmosphere, providing habitat) are the aggregated biogeochemical processes that determine the flows and transformations, which in turn deliver benefits to humans. Supporting services are defined from internal reservoir functions that maintain provisioning, regulating and cultural services. Natural capital defines the state of the inventory of stocks that supply flows of critical zone services to satisfy humans' needs. Two categories of economic valuation approaches (market-based and non-marked based) can be applied to estimate economic value of critical zone services.

(e.g. food); however, the actual use of the regulating (e.g. erosion control) and cultural services (e.g. spiritual value) are not intuitive (Thiele et al., 2020). In addition, some critical zone services are not easily accessible to humans and as a result may be under-valued. For example, geodiversity may be a valuable cultural service, but it requires interpretation through the specialist knowledge of geologists to translate this into information that is beneficial. We include methods of quantifying the benefits of flows of regulating and cultural services in Section 3.5 in this paper.

3.2. Framework linking biophysical processes and functions, anthropogenic drivers, critical zone services, stocks and flows and economic valuation techniques of Earth's critical zone

Understanding the relationship between biophysical processes and functions, anthropogenic drivers for value creation and critical zone services for delivery of benefits is fundamental to economic valuation of Earth's critical zone. The proposed interdisciplinary framework consists of six sections: Earth systems' concepts of biogeochemical cycles, critical zone structure and functions, anthropogenic drivers that influence critical zone processes and functions, critical zone services, indicators that are translated from stocks and flows of critical zone services, and the economic valuation methods for monetizing critical zone services (Fig. 2).

Coupled cycling. Earth's critical zone has two principle cycles: the geological cycle and the biological cycle that exhibit very different physical, spatial and temporal scales but are critical to understanding the complex evolution and dynamic functions of the critical zone to provide critical zone services to humans (Lin 2010). Both the geological cycle and biological cycle refer to the processes of producing, transporting, consuming and recycling materials (M), energy (E) and genetic information (I) that contribute to the structure and functions of Earth's critical zone (Banwart et al., 2019).

These two cycles interface through mass and flux balance. The geological cycle typically exhibits slow process rates integrated over large masses (rock and subsurface water) that are characteristic of the belowground components (e.g. of the shallow lithosphere). The biological cycle exhibits more intense rates of processes integrated over smaller reservoirs of mass (e.g. the vegetation and soil microbiome). Flux balance between the 2 cycles occurs at the interface between the internal components of the critical zone with geological cycling contribution dominantly to the functions of groundwater, biological cycling contributing dominantly to the function of soil, vegetation and their interactions with the atmosphere, and both geological and biological cycling contributing to the functions of surface water. As an example, the rate of supply of mineral P and K as nutrients for plant growth, from bedrock conversion to soil over geological time scales, can be comparable to the seasonal rate of P and K accumulation by plants through the net effect of uptake by plants roots and release by decay of plant litter in soil. Because of large rock and water mass and low process rates, the relative dynamic response time for the groundwater component is often much longer than the relative response time for change in mass stocks of the other components.

Biophysical structure and functions. There are five components of critical zone structure (see in Fig. 1): atmosphere, vegetation, soil, surface water and groundwater. The atmosphere of Earth's critical zone refers to the gaseous envelop surrounding the Earth's surface within the atmospheric boundary layer (Ridpath 2012; Keller 2019). The bulk volume of the atmospheric boundary layer is not a dominant habitat for life, yet it sustains life at Earth's surface (Fahy 2009). The benefits derived from the atmospheric boundary layer include provisioning of molecular oxygen that humans breathe and nitrogen for biological fixation into biomass, generating energy from wind, cleansing air quality and depositing and dispersing dissolved and particulate pollutants, and providing aesthetic sensual, intrinsic and existence value.

Vegetation is one of the above-ground and shallow sub-surface biomass components of Earth, which receives and processes solar radiation, water, carbon and geochemical fluxes (Banwart et al., 2019). The categories of vegetation types are various, including not only forests and grasslands, but also crops (Keesstra et al., 2018). Vegetation provides benefits to humans mainly through the function of CO_2 fixation and O_2 production by photosynthesis, nutrient transformation as biomass production, e.g. for food, collecting atmospheric deposition and releasing H_2O by evapotranspiration.

Soil is the central part of Earth's critical zone, acting actively to transmit mass, energy, and biodiversity downward to the groundwater, upward to the vegetation and atmosphere, and laterally to surface water (Banwart et al., 2017). Soil functions are the flows and transformations within soil that provide benefits to humans. In broad terms these functions include biomass production, nutrient transformations, C and N storage, water storage and transmission, and maintenance of biological habitat and a pool of genetic diversity (Banwart et al., 2017).

Surface water is one of the most important resources for human well-being (Reynaud and Lanzanova 2017). Surface water bodies supply benefits to humans through multiple functions including provisioning water, food, raw materials, regulating water quality, greenhouse gases and climate, mitigating floods, retaining sediment, controlling biodiversity and supplying cultural services.

Groundwater has been defined as all the subsurface water existing below the upper A and B pedological layers (Kovacs and Durand-Morat 2020), i.e. the water in the deeper parts of the unsaturated layer of sediments and in the zone of saturation (Neupane and Kumar 2020). It delivers benefits directly to humans through the following functions: storing and supplying freshwater, maintaining biodiversity and genetic resources, purifying pollutants and waste, regulating hydrological flow, mitigating floods and accompanying erosion, and contributing to regulating climate.

Anthropogenic drivers. In addition to tectonic forcing, weathering, fluid transport, and biological activity as highlighted by the NRC (National Research Council, 2001), human forcing is considered to have a fundamental impact on Earth's critical zone (Richter and Billings 2015). Changing soil thickness due to agricultural erosion, for example, illustrates the accelerated impacts caused by humans. The average rate of soil formation from bedrock weathering has been estimated as 1 mm or even less per year, while the rate of soil erosion has reached values 1-2 orders-of-magnitude greater in many regions because of human activities (Brantley et al., 2006; Egli et al., 2018; Montgomery 2007). Such an imbalance between the slow production of new soil (which is generally subsoil above fresh bedrock) and the accelerated loss of fertile topsoil has severe negative and irreversible (on generational timescales) consequences for the sustained functioning of the critical zone. Specifically, increased population and wealth with resulting land use intensification and climate change are the most prominently recognized anthropogenic drivers and threats to critical zone functions (Banwart et al., 2019).

3.3. Earth's critical zone services

When estimating the economic value of Earth's critical zone, the identification and classification of the relevant services provided by Earth's critical zone is the first step (MEA 2005a; Kumar et al., 2018; Nie et al., 2020). However, there have been few attempts to systematically identify and classify critical zone services. Field (2015) provided the first study. More recently, Nie (2020) carried out a pilot study on site-specific economic valuation of 14 critical zone services identified for the five compartments of Earth's critical zone described above, in an experimental catchment in China.

From previous studies (Costanza et al., 1997; Maes et al., 2016) we combined two approaches to develop the analysis of critical zone services. The first approach is to identify the ecosystem typology defined by Earth's critical zone, and the second is to define the typology of critical zone services provided by the identified components of Earth's critical zone (Maes et al., 2016). The first approach accounts for the dominant, physically distinct functional components within Earth's critical zone. The second clarifies the precise services provided by each component of Earth's critical zone.

Few studies have focused on the ecosystem services provided by the atmosphere. We found four (Thornes et al., 2010; Kendall et al., 2014; Richardson et al., 2017; Nie et al., 2020). Thornes et al. (2010) and Kendall (2014) presented twelve similar atmospheric services that are vital to human well-being and to the existence of the biosphere. Richardson et al. (2017) assessed the economic value of atmospheric stabilizing services of the critical zone. Nie (2020) estimated the economic value of air that humans breathe provided by the atmosphere. Based on these studies, we identified four services focusing on benefits directly useful to humans and considering the lower atmospheric boundary layer associated with Earth's critical zone.

Vegetation provides many direct ecosystem services for sustaining humans and their life quality (De Carvalho and Szlafsztein 2019). Previous work is reported from both the natural and social sciences, with a predominant focus on provisioning services (food provisioning, raw materials provisioning). We have integrated from this literature thirteen ecosystem services provided by vegetation.

Soil is the central interface of Earth's critical zone (Banwart et al., 2017); its ecosystem services have been defined during the past

Table 1
Earth's critical zone services.

Component	Provisioning	Regulating	Cultural
Atmosphere	Air that humans breathe	The cleansing capacity of the atmosphere and dispersion of air pollution	Aesthetic, sensual, intrinsic and existence value
	Direct use for power		
Vegetation	Food production	Carbon sequestration	Recreation and tourism services
	Raw materials	Climate regulation	Knowledge systems, cultural diversity, educational and aesthetic values
		Waste treatment	Spiritual and symbolic value
		Water regulation	
		Disturbance regulation	
		Erosion control	
		Pollination	
		Biological control	
Soil	Food production	Carbon sequestration	Recreation and tourism services
	Water storage and supply	Greenhouse gases regulation	Knowledge systems, cultural diversity, educational and aesthetic values
	Raw materials	Water regulation	Spiritual and symbolic value
	Platform for physical support	Filtering of nutrients and contaminants	
		Natural attenuation of pollutants	
		Biological control	
Surface water	Water storage and supply	Water purification and waste treatment	Recreation and tourism services
	Food production	Flood mitigation	Knowledge systems, cultural diversity, educational and aesthetic values
	Raw materials	Sediment retention	Spiritual and symbolic value
	Abiotic materials	Greenhouse gases regulation	
		Climate regulation	
		Biological control	
Groundwater	Freshwater storage and supply	Water purification and waste treatment	Recreation and tourism services
	Biodiversity and genetic resources	Hydrological regulation	Knowledge systems, cultural diversity, educational and aesthetic values
		Flood mitigation and erosion control	Spiritual and symbolic value
		Climate regulation	

Sources: Authors

decade from a relatively comprehensive framework for their classification. We identified thirteen ecosystem services provided by soil mainly based on this literature (Costanza et al., 1997; Dominati 2013; Jónsson et al., 2017).

We also distinguished the services provided by surface water including rivers, lakes and wetlands from those delivered by groundwater. A large variety of surface water related ecosystem services have been addressed by Maes et al. (2016), Egoh et al. (2012) and Grizzetti et al. (2016). However, the linkages between groundwater and ecosystem services are often not recognized and may be under-valued. We identified thirteen surface water related ecosystem services based on those studies mentioned above and nine groundwater related ecosystem services mainly based on Bergkamp and Cross (2006), Knüppe et al. (2016), Tuinstra et al. (2014), and Danielopol et al. (2003).

We based our classification of critical zone services on three categories (i.e., provisioning, regulating and cultural services) defined in the Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018). However, within this classification system, we explicitly include only these three classes of services because they are of direct benefit to humans. We explicitly exclude supporting services that help maintain and sustain the flows of benefits from the other three classes of services. This approach is to avoid double accounting, where the value of supporting services is intrinsically included within the value of the other three classes of services at the point of delivering benefits. Finally, we established an integrated list of services provided by Earth's critical zone (Table 1). The list of services we compiled here aims to define a spectrum of previously identified services derived from different components of Earth's critical zone, which can be amended or expanded with advancement in knowledge of critical zone processes and their interconnectivity.

The definitions and use of terms to describe ecosystem services vary across the published classification systems. Supplement 1 sets out the definitions and literature references of the critical zone services identified in this study. Among the references listed in Supplement 1, only two studies have identified critical zone services derived from the five components of Earth's critical zone, three have identified critical zone services provided by the atmosphere of Earth's critical zone, and thirteen have identified critical zone services derived from the groundwater of Earth's critical zone. The remaining literature was mainly focused on goods and services provided by the near surface components of vegetation, soil and surface water, of Earth's critical zone.

3.4. *Theoretical basis of economic valuation of Earth's critical zone*

The economic valuation techniques used in many studies of ecosystem services are based, either directly or indirectly, on attempts to estimate the unit value of each ecosystem service. From economic theory, general equilibrium models and dynamic models (You et al., 2018) have rarely been attempted in order to determine estimates of the value of ecosystem services. However, a partial equilibrium framework (Costanza et al., 1997) that has been widely used in practice including in the valuation of ecosystem services is adopted in this paper. Partial equilibrium theory is used to determine the total economic value (Gross Domestic Product) of goods and services in a nation's economy, and is also applied to determine the value of individual products or services in a market economy. The theory defines the relationship between price and the quantity of supply and demand for human-made, substitutable, typically marketed goods and services, with the supply curve as an upward sloping price curve and the demand curve as a downward sloping price curve, with increasing quantity (Fig. 3a). The intersection (P, Q) of the supply and demand curves is the equilibrium price (P) and quantity (Q) of the commodity where the market reaches equilibrium state. The intersection A of the demand curve and the y-axis represents the maximum price of consumers' willingness to pay for a good or service. Point C, where the supply curve and the y-axis intersect, is the minimum price regarding producers' willingness to sell a good or service.

There are three relevant areas represented on the diagram (Fig. 3) which are production cost, producer surplus (or net rent), and consumer surplus. The cost of producing a product is the area under the supply curve (area CBQ); the producer surplus (also termed net rent) is the area between the equilibrium price and the supply curve (area PBC); the consumer surplus, which is the value of benefit to the customer, is the area below the demand curve and above the price paid in the market (area ABP). When partial equilibrium theory is applied to national economies, another area on the graph, PBQC, defines the Gross Domestic Product. When the theory is applied to an individual good or service, the economic value can be defined in several ways. One definition is the sum of consumer and producer

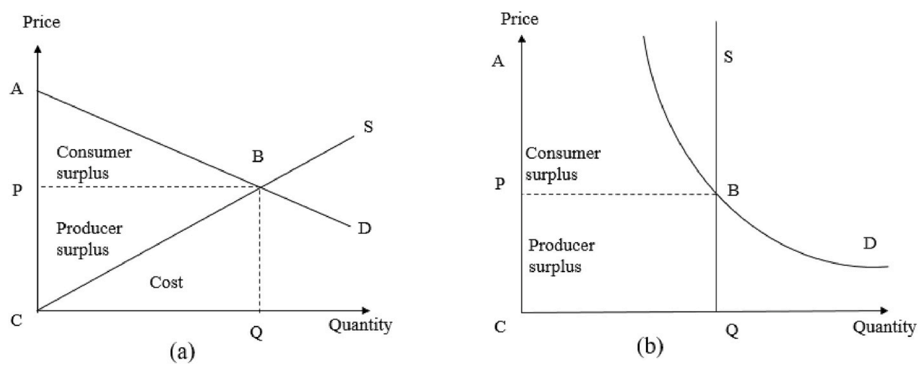

Fig. 3. Supply and demand curves, showing the equilibrium price where the curves intersect, and the corresponding definitions of cost, consumer surplus and producer surplus for normally traded goods and services (a) and ecosystem services which may not have a traded market (b).

surplus (ABC) and another is the producer surplus (PBC) or in the absence of information on the supply and demand curves, value is estimated by the price times quantity as a proxy value (area PBQC, Fig. 3). The total economic value (ABC) of a good or service can be greater or less than its market price times quantity (PBQC).

As the majority of ecosystem services are not manufactured and traded within a recognized market, their demand curve is complex and very difficult, if not impossible, to estimate. Many ecosystem services can be only substituted to a point (e.g. considered as non-renewable); therefore, it is postulated (Farley 2012) that the relationship between price and demand is more likely to exhibit behavior shown by the demand curve in Fig. 3b. In terms of the supply curve, as many ecosystem services cannot be increased or decreased instantaneously by actions of the economic system, supply is inelastic as represented by a nearly vertical curve (Cumming et al., 2014), as shown in Fig. 3b. Here the cost of production (point C) is zero, because many ecosystem services are public goods, and in conventional economic theory their production is considered cost-free. The producer surplus is the area under the market price, PBQC, which is equal to the equilibrium price times quantity. The consumer surplus is the area over and above the market price, ABP. The total economic value of the ecosystem service is the area under the demand curve, ABQC. Note that here the demand approaches infinity as the quantity available (supply) approaches zero (or some minimum necessary level of services). This means the maximum price (point A) of consumers' willingness to pay for ecosystem services can be infinite. As a consequence, the consumer surplus (ABP) as well as the total economic value (ABQC) is infinite. Therefore, we can only use equilibrium price times quantity (PBQC) as a proxy for the lower bound on economic value of ecosystem services.

The application of partial equilibrium theory also utilizes a further important concept, that of unit value, which defines the price associated with a good or service at a specific scale. It can refer, for example, to the price of a product in the market, the value of an object, or the aggregate value of one type of service that benefits many users. In this study we propose a methodology to estimate the unit value of Earth's critical zone based on this economic theory. We assume that the supply and demand curves for Earth's critical zone services look more like Fig. 3b than Fig. 3a, and we use price times quantity (PBQC) as a proxy for the unit value of each of the services provided by Earth's critical zone. The unit values multiplied by the physical scale (surface area, mass, volume or population) of the defined system delivering each critical zone service of interest and aggregating over all of the identified Earth's critical zone services, allows calculations that arrive at local, regional or global totals of the monetary value of Earth's critical zone.

3.5. Biophysical indicators

Many policy decisions rely on ecosystem service indicators and metrics to communicate the state (stocks and flows) of natural resources to inform management practices (Layke et al., 2012). Indicators and metrics are essential to demonstrate whether or not these services are being sustained or lost, their dependence on management practices, and how policies should be designed to ensure the continuous provision of ecosystem services and associated benefits to humans (Schröter et al., 2005; Layke et al., 2012; Egoh et al., 2012). The MEA (2005a) has demonstrated the need for such indicators. Recent reviews emphasized that these indicators need further improvement (Bateman et al., 2013; Cochran et al., 2020). Following this conclusion and considering the current advances in the natural sciences knowledge of Earth's critical zone, we propose to base the biophysical assessment of critical zone services on biophysical indicators and metrics rather than the currently used ecosystem services assessment tools.

In order to correctly understand and appropriately use the indicators and metrics of critical zone services, and more generally to structure the valuation, we have to analyse what biophysical information the indicators represent for sustaining the provisioning of critical zone services. To address this we proposed a simplified conceptual framework (presented in Fig. 4) for structuring the analysis and the classification of indicators of critical zone services. The framework includes the stocks of rock, water, gases and organisms of Earth's critical zone that deliver the actual flows of critical zone services, the efficiency of the processes and functions of Earth's critical zone in maintaining the flows that deliver the critical zone services, the sustainability of providing critical zone services, and the economic benefits of critical zone services. Here, efficiency defines that degree to which flows are sustained at a maximum or optimum value for human benefits (Kihara et al., 2020). Stocks define the potential of Earth's critical zone to provide critical zone services, and

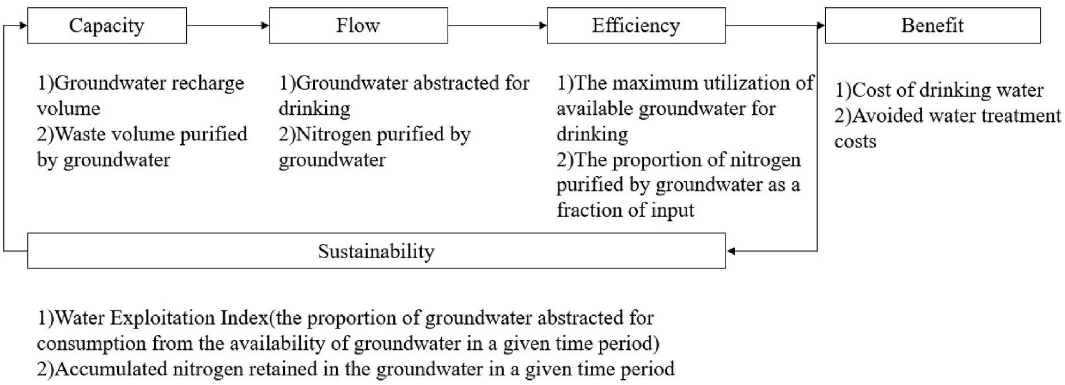

Fig. 4. Conceptual framework to classify indicators of critical zone services derived from groundwater. The diagram presents examples of indicators for the groundwater services of 1) freshwater storage and supply and 2) water purification and waste treatment.

their assessment relies on biophysical data (e.g. subsurface void volume filled with groundwater and also the rate of replenishment) (Sato et al., 2020). However, flows capture the actual use of the critical zone services, and their quantification requires the acquisition of socio-economic data (e.g. groundwater abstracted for drinking) (Langemeyer and Connolly 2020).

Sustaining the benefits to humans over time relies on the continuous provision of goods and services, while intensive exploitation pressures on the critical zone result in a high risk of failure to maintain optimum benefits (Manea et al., 2020). For this reason, it is important to consider the notion of sustainability of stocks and the resulting flows that benefit humans when assessing the critical zone services. In some cases, we suggest collecting biophysical indicators regarding the efficiency of the critical zone processes and functions that deliver critical zone services to and used by humans. The theoretical basis would come from natural sciences' understanding of what biophysical information the proxy represents for sustaining the stocks and flows of critical zone services. As an example, the mass representing 80 % of nitrate as pollution that could be purified by groundwater in a given time is an efficiency proxy of the water purification service provided by groundwater.

Many provisioning services are tangible goods (such as rice, fish, water) and can be measured and quantified relatively easily. Regulating services which are being integrated into economic markets or subject to government regulation, such as climate regulation from carbon sequestration provided by soil, water purification and waste treatment provided by surface water and groundwater, generally have more developed indicators and metrics than those services which do not have a built infrastructure or market analogue. However, many regulating services (e.g. the biological control of pests and diseases) are less tangible and cannot readily be quantified directly. Similarly, within cultural services, recreation and tourism services are traded in existing markets and have strong indicators and metrics; however, aesthetic, sensual, intrinsic and existence value, such as that provided by the atmosphere or landscape, is intangible and does not have an economic market. Also, it is not trivial to identify and quantify a suitable indicator for cultural services. In these cases, sometimes of less tangible services, we propose to use indicators on either sustainability or efficiency to assess critical zone services. For example, some degraded soils can be deficient in the functioning of filtering of nutrients and contaminants. Therefore, the amount of each potentially toxic element (e.g. transition metal levels based on mass per cent in dry soil and soil bulk density) accumulated in a given period can be used as a sustainability indicator of soil's service of filtering of nutrients and contaminants. Most crops' functional food quality (energy value, protein content, sugar content) provided by vegetation can be used as an efficiency indicator, while the amount of dry matter of crops per hectare per year measures the flow of food production.

Those biophysical indicators that convey the same information but are formulated differently should be only counted once in the economic valuation. In some cases, to take food production derived from surface water as an example, fish yield is used as a food production metric and should, therefore, not be included as a separate indicator for other services such as water quality.

Also, the biophysical indicators should only capture the service provided by the stocks that are determined by the structure and function of Earth's critical zone, and the biophysical metrics should differentiate and subtract the part of service coming from added or built capital (e.g. fertilizer invested in soil, fish aquaculture facilities built in the lake) to inform the provision of the service. For example, when quantifying the provision of food from vegetation, the influence of phosphorus (P) and nitrogen (N) fertilizer inputs, irrigation water and drainage must be distinguished from the total production and distinguished separately from that arising otherwise from critical zone processes. The biophysical indictors that are chosen in the valuation methods are based on an assumption that metric values representing good condition indicate a healthier and more resilient ecosystem that provides more services and maintains the capacity to provide them for the future. However, to what extent this is the fact requires detailed process understanding which, for many services, remains a research frontier.

Based on these criteria, we identified the majority of relevant indicators available to assess the biophysical value of critical zone services, which are summarized in Supplement 2. It should be noted, however, that this list does not capture all possible indicators to measure Earth's critical zone, but represents those that we have selected for the critical zone goods and services that we identified from literature review and summarized in Table 1.

3.6. Economic valuation techniques

Economic valuation is the process of measuring in monetary terms welfare changes associated with changes in environmental quality or level of provision of ecosystem services based on individual human preferences (Bateman et al., 2013). The economic valuation of critical zone services offers a common unit to represent the value of critical zone services by aggregating welfare changes derived from Earth's critical zone. This estimation facilitates economic decisions and financial markets to determine the economic value of the non-market goods and services of Earth's critical zone (Costanza et al., 1997; Daily 1997; Baveye et al., 2013; Hansjürgens et al., 2016; Lienhoop et al., 2018). The value of the world's ecosystem services and natural capital estimated by Costanza (1997) is a milestone in economic valuation of ecosystem services. Since then, economists have worked extensively on various economic valuation methods for monetizing ecosystem services and applied these approaches to a wide range of specific ecosystems (e.g. forests, lakes) (Liu et al., 2018).

Overall, there are two categories of economic valuation approaches: market-based and non-market based methods. Market-based valuation methods assess either the economic value or the avoided environmental impacts reflected in the price. This approach is based on the fact that individuals have observed preference for an ecosystem service that has already been traded in the existing market. These observed preferences are reflected through direct and/or indirect markets and are measured by various market-based approaches such as market price and replacement cost. Non-market based valuation methods attempt to elicit pre-existing preferences for a service that is not traded in well established markets (Guo et al., 2001). The basis of this method is that the economic value of a good or service can be elicited through the process of reasoned discourse with other members of society (Hattam et al., 2015). Non-market based approaches are able to measure both the revealed preferences through surrogate markets using for instance, hedonic pricing (captures a consumer's willingness to pay for perceived environmental differences) and travel cost (calculates willingness to pay for a constant price facility), and stated preferences through hypothetical markets employing methods such as contingent valuation, choice modelling and choice experiment. Another practical non-market based method to estimate the economic value of critical zone services is the value transfer approach. Value transfer means using economic estimates from previously obtained data to a new study, which values services provided by the ecosystem of interest at another location or time (Davidson 2013; Grizzetti et al., 2016). The hypothesis of this method is that the existing estimates of ecosystem services can be transferred to a different context. The methods for economic valuation available for critical zone services are summarized in Fig. 5.

Many economic valuation methods have been used to estimate the economic value of soil and water (surface water and groundwater) ecosystem services. Jónsson et al. (2016) reviewed 14 approaches for valuing soil ecosystem services. Grizzetti et al. (2016) summarized 7 valuation methods for estimating the economic value of water ecosystem services. These economic valuation methods encompass the standard accounting methods for estimating the economic value of ecosystem services, e.g. as summarized in Fig. 5. In this study we selected several economic valuation methods that have been accepted widely for comparing market and non-market value in economic decision-making, and uncontroversially have been applied in the previous literature to measure the economic value of critical zone services. Also, the techniques used to value each critical zone service are based on the biophysical metrics and indicators that are selected to represent stocks and flows of the services over time, and should be relevant for the chosen scale and land use (Dominati 2013). For example, many provisioning services of Earth's critical zone can be easily traceable through well-functioning markets; therefore, they can be estimated by using market-based valuation methods such as market price. For those services that have no effects on private goods or services traded in existing markets, non-market based valuation methods are available. For example, sediment retention in surface waters is not traded in the existing markets; however, there is a surrogate market providing replacement cost of removing the retained sediment. Therefore, this replacement cost in the surrogate market can be used as a price to estimate the economic value of sediment retention (Pizzol 2015).

For those critical zone services that lack data in one location but have abundant data in a similar scenario, we adopt the value transfer method to estimate their economic value. For example, air quality accounts for little weight in developing countries, as a result there are very few economic data directly related to air quality regulation services. However, developed countries that have well-established data on the resulting health impacts and costs of, e.g. respiratory illness arising from particulate air pollution, hold many relevant data sets that are available for the economic valuation of this ecosystem service. The transfer errors when using value transfer methods, for example, the economic value in different countries is affected by income differences, should be considered.

In the specific case of economic valuation of atmospheric services, the provisioning services can be monetized by using non-market based valuation methods such as hedonic pricing. The regulating service of the cleansing capacity of the atmosphere and dispersion of air pollution can be monetized through the replacement cost method (e.g. control cost of pollutants). As aesthetic, sensual, intrinsic and existence value are not traded in the established market, non-market approaches such as travel cost derived from surrogate markets and contingent valuation method simulated from hypothetical markets can be adopted for the economic valuation.

Among the three categories of critical zone services (provisioning, regulating and cultural), cultural services are frequently underestimated in the literature of economic valuation of ecosystem services (Nepal et al., 2018). This may originate from the characteristic of cultural services, which are created through experiential interactions between humans and ecosystems rather than as priority products of nature that people utilize to enhance their well-being, making it intangible and difficult to estimate the economic value. The existing literature on the monetary valuation of cultural services is largely limited to applying contingent valuation, travel cost, damage cost and hedonic pricing approaches to estimate the economic value of recreation and tourism services. However, the economic valuation methods for other important cultural services such as knowledge systems, cultural diversity, educational and aesthetic values, spiritual and symbolic value are rarely studied. This remains a research frontier.

The principal economic valuation approaches that are available for critical zone services, relevant for each of 5 biophysical

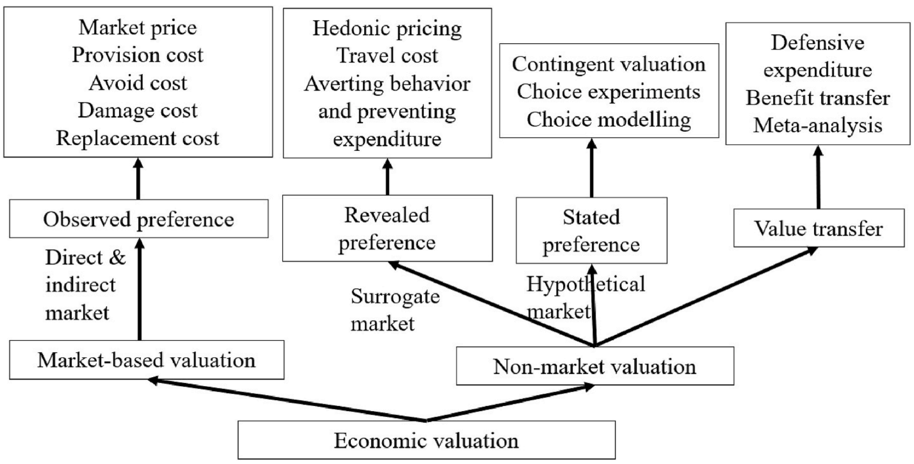

Fig. 5. Schematic classification of the different methods that have been developed for the economic valuation of ecosystem services.

components, are listed in Supplement 3. However, this compilation is not comprehensive and there are additional economic valuation methods that can be included to calculate the economic value of critical zone services.

3.7. A case study of economic valuation of Earth's critical zone

Table 2 summarizes the results of a pilot study of economic valuation of Earth's critical zone in the Zhangxi catchment, Zhejiang, China (Nie et al., 2020) that applied the partial equilibrium approach and the methodology described in this study.

The study area of Zhangxi catchment occupies an area of 91.59 km^2 and the main land cover type is forest (76.98 %). Crude drug, vegetables and fruits are the main agricultural products in the Zhangxi catchment. The Gross Domestic Product (GDP) of the Zhangxi catchment was USD 431 million in 2018. In order to estimate the economic value of Earth's critical zone at the location of Zhangxi catchment, fourteen critical zone services were identified, including services that would otherwise have been excluded, derived from the atmospheric boundary layer and groundwater of Earth's critical zone (Table 2) but excluding supporting services. The estimation was based on the biophysical indicators, economic valuation techniques and data availability. The estimated economic value of Earth's critical zone of Zhangxi catchment was USD 116 million, accounting for 0.27 times of its GDP (Nie et al., 2020). This fraction of GDP is lower than that calculated as the fraction based on the value of global ecosystem services (Costanza et al., 1997) but similar to the estimate made by classical economists, indicating Earth's critical zone provides economic value through a range of critical zone services (Nie et al., 2020). The study deals with a real, site-specific example and demonstrates how such an economic valuation method demonstrated in this study is possible in practice.

4. Conclusions and future work

This paper developed a methodology for economic valuation of Earth's critical zone as a specific physical system that supplies most life-sustaining resources as benefits to humans. This method includes the advances in the natural sciences' knowledge of Earth's critical zone and the current thinking on ecosystem services. Incorporation of Earth's critical zone into ecosystem service valuation concepts expands the currently predominant focus on the above-ground landscape, allowing a more comprehensive valuation of services that arise from the integrated functioning of the whole of the critical zone. Defining critical zone benefits as those derived from stocks and flows contained within Earth's critical zone that deliver services to humans is a conceptual advance that allows a generalized definition and clear delineation of the critical zone as the terrestrial component of the Earth system upon which humans depend. This development enables a useful conceptual advance and improved quantitative methodology as proposed by this manuscript. We

Table 2
Economic valuation of Earth's critical zone.

Earth's critical zone services	Biophysical indicators	Scale	Unit price	Economic value ($USD \cdot yr^{-1} \cdot 10^{-6}$)	TEV[a] ($USD \cdot yr^{-1} \cdot 10^{-6}$)
Atmosphere					4.94
Air that humans breathe	5475 $m^3 \cdot person^{-1} \cdot yr^{-1}$	47,178 persons	\$0.018 $m^{-3} \cdot person^{-1} \cdot day^{-1}$	4.94	
Vegetation					96.17
Food production	Yield ($kg \cdot ha^{-1} \cdot yr^{-1}$)	ha	Market prices	88.17	
Climate regulation	The climatic adjustment ecosystem value of forest in terrestrial China	70.51 km^2	\$360.89 ha^{-1} yr^{-1}	2.55	
Waste treatment	10,110 kg $ha^{-1} \cdot yr^{-1}$	70.51 km^2	\$25.68 t^{-1}	1.84	
Water regulation	192.4 mm	73.06 km^2	\$0.02 m^{-3}	0.27	
Erosion control	1060 t $km^{-2} \cdot yr^{-1}$	170.51 km^2	\$1.96 t^{-1}	0.15	
Biological control	Shannon-Wiener index<1	70.51 km^2	\$453.17 ha^{-1} yr^{-1}	3.19	
Soil					7.72
Carbon sequestration	19.1 g kg^{-1} (0–10 cm) 13.9 g kg^{-1} (10–20 cm)	86.08 km^2	\$50 t^{-1}	0.42	
Filtering of nutrients and contaminants	0.4–4.5 g kg^{-1} (0–10 cm) 0.1–2.73 g kg^{-1} (10–20 cm)	86.08 km^2	\$302.11 t^{-1}	7.3	
Surface water					5.42
Water storage and supply	3800 $m^3 \cdot day^{-1}$	365 $day \cdot yr^{-1}$	\$0.07 m^{-3}	0.11	
Water purification and waste treatment	COD:190.1 t yr^{-1} Ammonia nitrogen:15.24 t yr^{-1}	0.73 km^{-2}	\$709.59 t^{-1} \$1880.89 t^{-1}	2.29	
Recreation and tourism services	0.1–0.15 million tourists	Lijiakeng village		3.02	
Groundwater					1.89
Fresh water storage and supply	268.2 mm	91.59 km^2	\$0.07 m^{-3}	1.85	
Water purification and waste treatment	1.71 mg L^{-1}	91.59 km^2	\$6 kg^{-1}	0.04	
Total					116.14

[a] TEV represents Total Economic Value.
Sources: Adapted from Nie et al. (2020).

argue that considering the whole of the critical zone as a specific physical system improves the understanding of how critical zone functioning benefits humans, clarifies the inventory of stocks and flows and enables decision-makers to better predict anticipated deliveries of ecosystem services, particularly in response to human forcing that propagates impacts throughout the whole of the critical zone. Quantitative methods for the dynamic modelling and simulation of the interconnected critical zone processes and functions over the coming decade (Banwart et al., 2019) offers a potential way forward to integrate quantitative biophysical information with valuation techniques that may offer advances in full equilibrium models for valuation of the critical zone. This becomes particularly important as we use scientific evidence from critical zone research to help address growing societal needs for resources in the face of the anthropogenic drivers of increased population, land use intensification and climate change.

We provide an interdisciplinary framework that links biophysical processes and functions, anthropogenic drivers for value creation, critical zone services for delivery of benefits to humans and economic valuation techniques for monetizing Earth's critical zone. This conceptual framework clearly demonstrates how Earth's critical zone provides benefits to humans and how important the dependence of human wellbeing is on the integrated functioning of the critical zone as a whole. We consider five distinct physical components of critical zone structure as human habitat: atmosphere, vegetation, soil, surface water and groundwater that ensure the provision of critical zone services to humans. Following this approach, we identified from literature review a number of services derived from Earth's critical zone. Based on partial equilibrium theory we proposed a methodology for location-specific economic valuation of Earth's critical zone.

The proposed methodology suggests selecting proxies/indicators of critical zone services to assess their biophysical value. The approach also includes the economic valuation techniques for monetizing each critical zone service considering the spatial scale of application. These valuation methods vary significantly and should be considered critically. Because all of these economic valuation methods estimate the current economic value of Earth's critical zone and neglect future generations (Bachmann and van der Kamp 2014), the discount rate should be considered when estimating the economic value of critical zone services over specified time spans.

Economic valuation of Earth's critical zone provides a quantitative management tool that draws on recent advances from the natural sciences and enables economists and policy makers to more transparently enumerate the provision of services from the whole of Earth's critical zone. In addition, valuing Earth's critical zone by performing biophysical assessment and economic valuation collaboratively may highlight important, but otherwise neglected, benefits for society and boost awareness and inclusion in economic decisions of the interdependence of nature and people. However, the integration of biophysical and economic approaches and data availability remains a major challenge and is highlighted as a current characteristic of this approach.

Author contributions

Conceptualization and methodology, W.N., S.A.B. and H.Y.G; Writing—original draft preparation, W.N.; Writing—review & editing, S.A.B.; Supervision, S.A.B.; Project administration, S.A.B.; Funding acquisition, S.A.B.

Funding

This research was funded by the China Scholarship Council, grant number 201804920043 and the UK-China Critical Zone Observatory program, funded by the UK Research and Innovation, Natural Environment Research Council, grant numbers NE/N007514/1, NE/N007514/2 and NE/S009124/1.

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.

Acknowledgements

J. Martin-Ortega, University of Leeds provided constructive critical input to an early version of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2021.100654.

References

Bachmann, Till M., van der Kamp, Jonathan, 2014. 'Environmental cost-benefit analysis and the EU (European Union) Industrial Emissions Directive: exploring the societal efficiency of a DeNOx retrofit at a coal-fired power plant. Energy 68, 125–139.

Banwart, Steve, 2011. 'Save our soils. Nature 474, 151–152.

Banwart, Steven A., Bernasconi, Stefano M., Blum, Winfried EH., Danielle Maia de Souza, Chabaux, François, Duffy, Christopher, Kercheva, Milena, Pavel Krám, Lair, Georg J., Lundin, Lars, 2017. 'Soil functions in Earth's critical zone: key results and conclusions. In: Advances in Agronomy. Elsevier.

Banwart, Steven A., Nikolaidis, Nikolaos P., Zhu, Yong-Guan, Peacock, Caroline L., Sparks, Donald L., 2019. 'Soil functions: connecting earth's critical zone'. Annu. Rev. Earth Planet Sci. 47, 333–359.
Bateman, Ian J., Harwood, Amii R., Mace, Georgina M., Watson, Robert T., Abson, David J., Andrews, Barnaby, Amy, Binner, Crowe, Andrew, Day, Brett H., Steve, Dugdale, 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. Science 341, 45–50.
Baveye, Philippe C., Baveye, Jacques, Gowdy, John, 2013. 'Monetary valuation of ecosystem services: it matters to get the timeline right. Ecol. Econ. 95, 231–235.
Brantley, S.L., Fletcher, R.C., Buss, H., Moore, J., Hausrath, E., Navarre, A., Lebedeva, M., White, A.F., 2006. 'Weathering from the soil profile to the watershed: what controls the weathering advance rate? Geochem. Cosmochim. Acta 70, 1-1.
Cochran, Ferdouz, Daniel, Jessica, Jackson, Laura, Neale, Anne, 2020. Earth observation-based ecosystem services indicators for national and subnational reporting of the Sustainable Development Goals. Rem. Sens. Environ. 244, 111796.
Costanza, Robert, Ralph, d'Arge, De Groot, Rudolf, Farber, Stephen, Grasso, Monica, Hannon, Bruce, Limburg, Karin, Naeem, Shahid, Robert, V O'neill, Paruelo, Jose, 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, Robert, De Groot, Rudolf, Sutton, Paul, Van der Ploeg, Sander, Anderson, Sharolyn J., Kubiszewski, Ida, Farber, Stephen, Turner, R Kerry, 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158.
Cumming, Oliver, Elliott, Mark, Overbo, Alycia, Bartram, Jamie, 2014. 'Does global progress on sanitation really lag behind water? An analysis of global progress on community-and household-level access to safe water and sanitation. PloS One 9, e114699.
Daily, Gretchen C., 1997. Nature's Services. Island Press, Washington, DC).
Danielopol, Dan L., Griebler, Christian, Gunatilaka, Amara, Notenboom, Jos, 2003. 'Present state and future prospects for groundwater ecosystems. Environ. Conserv. 30, 104–130.
Davidson, Marc D., 2013. On the relation between ecosystem services, intrinsic value, existence value and economic valuation. Ecol. Econ. 95, 171–177.
De Carvalho, Mendonça, Roberta, Fabian Szlafsztein, Claudio, 2019. 'Urban vegetation loss and ecosystem services: the influence on climate regulation and noise and air pollution. Environ. Pollut. 245, 844–852.
De Groot, Rudolf, Brander, Luke, Sander Van Der Ploeg, Costanza, Robert, Bernard, Florence, Leon, Braat, Christie, Mike, Crossman, Neville, Ghermandi, Andrea, Hein, Lars, 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61.
del Río-Mena, Trinidad, Willemen, Louise, , Ghirmay Tsegay Tesfamariam, Otto, Beukes, Nelson, Andy, 2020. Remote sensing for mapping ecosystem services to support evaluation of ecological restoration interventions in an arid landscape. Ecol. Indicat. 113, 106182.
Dominati, Estelle J., 2013. 'Natural Capital and Ecosystem Services of Soils', *Ecosystem Services in New Zealand—Conditions and Trends*. Manaaki Whenua Press, Lincoln, New Zealand, pp. 132–142.
Egli, Markus, Hunt, Allen G., Dahms, Dennis, Raab, Gerald, Derungs, Curdin, Raimondi, Salvatore, Fang, Yu, 2018. 'Prediction of soil formation as a function of age using the percolation theory approach. Frontiers in Environmental Science 6.
Egoh, Benis N., Patrick, J O'Farrell, Charef, Aymen, Gurney, Leigh Josephine, Koellner, Thomas, Henry, Nibam Abi, Egoh, Mody, Willemen, Louise, 2012. An African account of ecosystem service provision: use, threats and policy options for sustainable livelihoods. Ecosyst. Serv. 2, 71–81.
Ehrlich, Paul, Ehrlich, Anne, 1981. 'Extinction: the Causes and Consequences of the Disappearance of Species.
Fahy, Frank, 2009. Air: the Excellent Canopy. Horwood Publishing.
Farley, Lisa, 2012. 'Analysis on air: a sound history of Winnicott in wartime. Am. Imago 69, 449–471.
Field, Jason P., Breshears, David D., Law, Darin J., Villegas, Juan C., López-Hoffman, Laura, Brooks, Paul D., Chorover, Jon, Barron-Gafford, Greg A., Gallery, Rachel E., Litvak, Marcy E., 2015. 'Critical Zone services: expanding context, constraints, and currency beyond ecosystem services. Vadose Zone J. 14.
Gagnon, John H., 1973. Man's impact on the global environment: assessment and recommendations for action. In: JSTOR.
Grizzetti, Bruna, Lanzanova, Denis, Liquete, Camino, Arnaud, Reynaud, Cardoso, A.C., 2016. Assessing water ecosystem services for water resource management. Environ. Sci. Pol. 61, 194–203.
Guo, Zhongwei, Xiao, Xiangming, Gan, Yaling, Zheng, Yuejun, 2001. 'Ecosystem functions, services and their values–a case study in Xingshan County of China. Ecol. Econ. 38, 141–154.
Haines-Young, R., Potschin, M.B., 2018. Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. Available from. www.cices.eu.
Hansjürgens, Bernd, Kehl, Christoph, Loft, Lasse, 2016. The economic approach to ecosystem services and biodiversity: policy design and institutions matter. GAIA-Ecological Perspectives for Science and Society 25, 174–181.
Hattam, Caroline, Böhnke-Henrichs, Anne, Tobias, Börger, Burdon, Daryl, Hadjimichael, Maria, Delaney, Alyne, Atkins, Jonathan P., Garrard, Samantha, Austen, Melanie C., 2015. 'Integrating methods for ecosystem service assessment and valuation: mixed methods or mixed messages? Ecol. Econ. 120, 126–138.
Institute, World Resources, 2000. A Guide to World Resources, 2000-2001, People and Ecosystems: the Fraying Web of Life.
Jónsson, J.Ö.G., Davíðsdóttir, B., Nikolaidis, N.P., 2017. 'Valuation of soil ecosystem services. Advances in Agronomy. Elsevier.
Jónsson, Jón Örvar G., Davíðsdóttir, Brynhildur, 2016. 'Classification and valuation of soil ecosystem services. Agric. Syst. 145, 24–38.
Jordan, Philip, Rippey, Brian, Anderson, N John, 2001. Modeling diffuse phosphorus loads from land to freshwater using the sedimentary record. Environ. Sci. Technol. 35, 815–819.
Kabubo-Mariara, Jane, Mulwa, Richard, 2019. 'Adaptation to climate change and climate variability and its implications for household food security in Kenya. Food Security 11, 1289–1304.
Keesstra, Saskia, Nunes, Joao, Novara, Agata, Finger, David, Avelar, David, Kalantari, Zahra, Cerdà, Artemi, 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009.
Keller, C Kent, 2019. 'Carbon exports from terrestrial ecosystems: a critical-zone framework. Ecosystems 22, 1691–1705.
Kendall, Michaela, Kothencz, Gyula, Stahl-Timmins, Will, Thornes, John, 2014. 'Atmospheric Resource Impact Assessment (ARIA) an inventory for evaluating ecosystem services derived from the atmosphere. Prog. Phys. Geogr. 38, 414–430.
Kihara, J., Bolo, P., Kinyua, M., Nyawira, S.S., Sommer, R., 2020. Soil health and ecosystem services: lessons from sub-Sahara Africa (SSA). Geoderma 370, 114342.
Knüppe, Katherine, Pahl-Wostl, Claudia, Vinke-de Kruijf, Joanne, 2016. Sustainable groundwater management: a comparative study of local policy changes and ecosystem services in South Africa and Germany. Environ. Pol. Govern. 26 (1), 59–72. https://doi.org/10.1002/eet.1693.
Kovacs, Kent F., Durand-Morat, Alvaro, 2020. The influence of lateral flows in an aquifer on the agricultural value of groundwater. Nat. Resour. Model. 33, e12266.
Kumar, Praveen, Phong, VV Le, An, Thanos Papanicolaou, Rhoads, Bruce L., Anders, Alison M., Stumpf, Andrew, Christopher, G., Wilson III, E Arthur Bettis, Blair, Neal, Adam, S Ward, 2018. 'Critical transition in critical zone of intensively managed landscapes. Anthropocene 22, 10–19.
Langemeyer, Johannes, Connolly, James JT., 2020. 'Weaving notions of justice into urban ecosystem services research and practice. Environ. Sci. Pol. 109, 1–14.
Latour, Bruno, 2014. 'Some advantages of the notion of "Critical Zone" for geopolitics. Procedia Earth and Planetary Science 10, 3–6.
Latour, Bruno, 2018. Down to Earth: Politics in the New Climatic Regime. John Wiley & Sons.
Layke, Christian, Mapendembe, Abisha, Brown, Claire, Walpole, Matt, Winn, Jonathan, 2012. 'Indicators from the global and sub-global Millennium Ecosystem Assessments: an analysis and next steps. Ecol. Indicat. 17, 77–87.
Lienhoop, Nele, Schröter-Schlaack, Christoph, 2018. 'Involving multiple actors in ecosystem service governance: exploring the role of stated preference valuation. Ecosyst. Serv. 34, 181–188.
Lin, Hangsheng, 2010. Earth's Critical Zone and hydropedology: concepts, characteristics, and advances. Hydrol. Earth Syst. Sci. 14, 25.
Liu, Xinyu, Guy, Ziv, Bakshi, Bhavik R., 2018. 'Ecosystem services in life cycle assessment-Part 2: adaptations to regional and serviceshed information'. J. Clean. Prod. 197, 772–780.
Maes, Joachim, Liquete, Camino, Teller, Anne, Erhard, Markus, Luisa Paracchini, Maria, José, I Barredo, Grizzetti, Bruna, Cardoso, Ana, Somma, Francesca, Petersen, Jan-Erik, 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosyst. Serv. 17, 14–23.
Manea, E., Bianchelli, S., Fanelli, E., Danovaro, R., Gissi, E., 2020. 'Towards an ecosystem-based marine spatial planning in the deep mediterranean sea. Sci. Total Environ. 715, 136884.

Martin, Carol L., Momtaz, Salim, Gaston, Troy, Moltschaniwskyj, Natalie A., 2020. 'Estuarine cultural ecosystem services valued by local people in New South Wales, Australia, and attributes important for continued supply. Ocean Coast Manag. 190, 105160.
MEA, 2005a. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.
MEa, Millennium Ecosystem Assessment, 2005b. 'Ecosystems and Human Well-Being: Synthesis. Island, Washington, DC.
Montgomery, David R., 2007. 'Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. Unit. States Am. 104, 13268–13272.
National Research Council, 2001. Basic Research Opportunities in Earth Science. National Academies Press.
Nepal, Mani, Rai, Rajesh Kumar, Das, Saudamini, Bhatta, Laxmi Dutt, Kotru, Rajan, Singh Khadayat, Madan, Singh Rawal, Ranbeer, GCS Negi, 2018. 'Valuing cultural services of the kailash sacred landscape for sustainable management. Sustainability 10, 3638.
Neupane, Ram, P., Kumar, Sandeep, 2020. 'Water 222 Rn for evaluating the variation in groundwater inflows to discharge of the Big Sioux River in different flow periods. Sustain. Water Res. Manag. 6, 13.
Nie, Wan, Guo, Hongyan, Yang, Lei, Xu, Yaoyang, Li, Gang, Ruan, Xiaohong, Zhu, Yongguan, Chen, Liding, Banwart, Steven A., 2020. 'Economic valuation of Earth's critical zone: a pilot study of the Zhangxi catchment, China. Sustainability 12, 1699.
Pizzol, Massimo, 2015. 'Life cycle assessment and the resilience of product systems. J. Ind. Ecol. 19, 296–306.
Rawlins, Jonathan M., Willem, J De Lange, Fraser, Gavin CG., 2018. An ecosystem service value chain analysis framework: a conceptual paper. Ecol. Econ. 147, 84–95.
Reynaud, Arnaud, Lanzanova, Denis, 2017. A global meta-analysis of the value of ecosystem services provided by lakes. Ecol. Econ. 137, 184–194.
Richardson, M., Kumar, P., 2017. Critical zone services as environmental assessment criteria in intensively managed landscapes. Earth's Future 5 (6), 617–632.
Richter, Daniel deB., Billings, Sharon A., 2015. ''One physical system': tansley's ecosystem as Earth's critical zone'. New Phytol. 206, 900–912.
Ridpath, Ian, 2012. A Dictionary of Astronomy. Oxford University Press.
Sannigrahi, Srikanta, Zhang, Qi, Joshi, P.K., Sutton, Paul C., Keesstra, Saskia, Roy, P.S., Pilla, Francesco, Basu, Bidroha, Wang, Ying, Jha, Shouvik, 2020. Examining effects of climate change and land use dynamic on biophysical and economic values of ecosystem services of a natural reserve region. J. Clean. Prod. 257, 120424.
Sato, Masaaki, Nanami, Atsushi, Bayne, Christopher J., Makino, Mitsutaku, Hori, Masakazu, 2020. 'Changes in the potential stocks of coral reef ecosystem services following coral bleaching in Sekisei Lagoon, southern Japan: implications for the future under global warming. Sustain. Sci. 1–21.
Schröter, Dagmar, Cramer, Wolfgang, Leemans, Rik, Colin Prentice, I., Araújo, Miguel B., Nigel, W Arnell, Bondeau, Alberte, Bugmann, Harald, Carter, Timothy R., Gracia, Carlos A., 2005. 'Ecosystem service supply and vulnerability to global change in Europe. Science 310, 1333–1337.
Sukhdev, Pavan, Wittmer, Heidi, Schröter-Schlaack, Christoph, Nesshöver, Carsten, Bishop, Joshua, Brink, P ten, Gundimeda, Haripriya, Kumar, Pushpam, Simmons, Ben, 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: a Synthesis of the Approach, Conclusions and Recommendations of TEEB. UNEP, Ginebra (Suiza)).
Tansley, Arthur G., 1935. The use and abuse of vegetational concepts and terms. Ecology 16, 284–307.
Thiele, Julia, Albert, Christian, Hermes, Johannes, von Haaren, Christina, 2020. Assessing and quantifying offered cultural ecosystem services of German river landscapes. Ecosyst. Serv. 42, 101080.
Thornes, John, Bloss, William, Bouzarovski, Stefan, Cai, Xiaoming, Chapman, Lee, Clark, Julian, Dessai, Suraje, Sen, Du, van der Horst, Dan, Kendall, Michaela, 2010. 'Communicating the value of atmospheric services. Meteorol. Appl. 17, 243–250.
Tuinstra, Jaap, Joke van Wensem, 2014. 'Ecosystem services in sustainable groundwater management. Sci. Total Environ. 485, 798–803.
Vallecillo, Sara, La Notte, Alessandra, Zulian, Grazia, Ferrini, Silvia, Maes, Joachim, 2019. 'Ecosystem services accounts: valuing the actual flow of nature-based recreation from ecosystems to people. Ecol. Model. 392, 196–211.
Xiang, Hengxing, Wang, Zongming, Mao, Dehua, Zhang, Jian, Xi, Yanbiao, Du, Baojia, Zhang, Bai, 2020. 'What did China's national wetland conservation program achieve? Observations of changes in land cover and ecosystem services in the sanjiang plain. J. Environ. Manag. 267, 110623.
You, Soojin, Kim, Min, Lee, Junga, Chon, Jinhyung, 2018. Coastal landscape planning for improving the value of ecosystem services in coastal areas: using system dynamics model. Environ. Pollut. 242, 2040–2050.
Zhong, Qicheng, Zhang, Lang, Zhu, Yi, Cecil Konijnendijk van den Bosch, Han, Jigang, Zhang, Guilian, Li, Yuezhong, 2020. 'A conceptual framework for ex ante valuation of ecosystem services of brownfield greening from a systematic perspective. Ecosys. Health Sustain. 6, 1743206.