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Review Paper

The geosystem services concept – What is it and can it support subsurface planning?

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ABSTRACT

The subsurface is a multifunctional natural resource. However, a mindset of "out of sight, out of mind" and a first-come-first-served principle are prevalent when accessing these resources, compromising fair intergenerational and intragenerational distribution and sustainable development. As with the ecosystem services (ES) concept, which acknowledges the contribution of the living part of nature to human well-being, the concept of geosystem services (GS) has been suggested as a way to highlight abiotic services and services provided by the subsurface. The overall aim of this study was to review current definitions of GS and their categorisation, and to suggest how the concept of GS can support subsurface planning. A systematic literature review on GS was carried out following the PRISMA protocol drawing from the Scopus database. The emerging picture from the reviewed articles is that the GS concept is both one of novelty and one currently showing inconsistency, with two prominent definitions: A) GS are abiotic services that are the direct result of the planet's geodiversity, independent of the interactions with biotic nature – there is no differentiation between suprasurface and subsurface features, and B) GS provide benefits specifically resulting from the subsurface. Thirty-one out of thirty-nine GS listed in the reviewed literature are included in the abiotic extension of the common ES framework CICES v5.1, but some essential services are omitted. A unified definition of GS is desirable to build a common framework for classifying and describing GS, potentially following the CICES structure for ES. Such a framework can support systematic inclusion of GS in planning processes and contribute to improved subsurface planning. In planning practice, there are examples of important GS that are already included under the ES umbrella because planners are aware of their importance but a comprehensive framework to handle these services is lacking.

1. Introduction

The subsurface is not only a foundation on which all human infrastructure relies, and which offers opportunities to create a better living environment, it is also a multifunctional natural resource. Apart from physical space, the subsurface can, for example, provide and store water, energy and materials, provide habitats for ecosystems, act as support for surface life, and serve as a repository for cultural and geological heritage (de Mulder et al., 2012; van Ree and van Beukering, 2016; Volchko et al., 2020). Globally, the first-come-first-served principle often applies to accessing the resources in the subsurface (e.g. Admiraal and Cornaro, 2016; Bartel and Janssen, 2016; Bobylev, 2009; Dick et al., 2019; Stones and Heng, 2016; Tengborg and Sturk, 2016), meaning that the first claim on the subsurface gets access and later claims are either not possible or need to be adapted. Because claims on the subsurface are sometimes incompatible, short-term uses can conflict with long-term uses and hinder future development which may compromise fair intergenerational and intragenerational distribution of these resources and

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jeopardising sustainable development. Due to rapid urbanisation and densification of urban areas, conflicting interests are likely to become even more common (e.g. Admiraal, 2006; Dick et al., 2019). A dilemma with subsurface resources is that they are often hidden from plain sight and, as such, invisible to most non-experts. Long-term strategic planning supported by relevant policy and regulation is therefore needed to overcome the first-come-first-served principle and to avoid individual projects unintentionally dictating future uses of the subsurface. Spatial planning needs to be developed to take the subsurface into consideration to a greater degree, recognising the opportunities as well as potential risks in plans (Hooimeijer and Maring, 2018; Norrman et al., 2016), and properly planning the use of subsurface resources (e.g., de Mulder et al., 2012; Dick et al., 2019; Norrman et al., 2021; van der Meulen et al., 2016b).

Ecosystem services (ES) is a concept that has brought attention to other complex and less obvious benefits that humans derive from nature. Although, in practice, not yet fully integrated into spatial planning, the concept of ecosystem services is widely accepted and embedded in global and national environmental policies to make the value of ecosystems visible and acknowledged in decision-making (e.g. Carpenter et al., 2009; Cornell, 2011). The ecosystem services concept has been used both to raise awareness and integrate various perspectives or disciplines into environmental management (i.e. functioning as a boundary object[1] e.g. Ainscough et al., 2019), and to integrate ES into environmental accounting using monetary valuation (e.g. the Common International Classification of Ecosystem Services (CICES), Haines-Young and Potschin, 2010, 2011, 2013, Haines-Young and Potschin-Young, 2018). The Millennium Ecosystem Assessment (MA) framework classifies four categories of ecosystem services: regulating, provisioning, cultural and supporting services. The latter is, however, controversial in ecosystem services frameworks from an economic point of view, because of the inherent risk of double counting and is for example omitted from CICES (e.g., Braat and de Groot, 2012; Haines-Young and Potschin-Young, 2018).

Ecosystem services are, by definition, the contributions that ecosystems make to human well-being, but services rendered by the non-living (abiotic) parts of ecosystems, including those derived from the subsurface, are often neglected in ecosystem services classification systems (van der Meulen et al., 2016a; van Ree and van Beukering, 2016). An explanation suggested by van Ree et al (2017) for this lack of inclusion of abiotic parts of ecosystems is that ecologists and biologists constituted a predominant group of the scientists involved in the development of the ecosystem services concept and that this indirectly caused other disciplines (e.g., geology, biogeochemistry, geomorphology, and geohydrology) to be underrepresented. However, ecosystems are not independent of abiotic nature (biophysical structures and processes) or its geodiversity, and the boundary between abiotic and biotic services is usually blurred (Fox et al., 2020). In the CICES classification from 2013 (CICES, V4.1, Haines-Young and Potschin, 2013), abiotic services were removed, but in the current version of the CICES framework (CICES V5.1, Haines-Young and Potschin-Young, 2018), they have been reinstated as an abiotic extension listing 35 abiotic services.

Some abiotic services associated with the subsurface, such as the provisioning of minerals, and fossil resources such as oil and gas, result in goods that are traded on commodity markets. Market prices are an obvious sign of the instrumental value to humans of these services, although market prices might differ substantially from the full economic value due to ignoring externalities such as pollution from extraction and use. Other abiotic services, such as the potential to store carbon dioxide or to retain water to prevent flooding, are not usually traded in markets, suggesting that there is a risk that their value is being overlooked in decision-making processes. The omission of abiotic services in ecosystem services frameworks is particularly notable in regard to the subsurface (van der Meulen et al., 2016a; van Ree and van Beukering, 2016).

Although biodiversity and ecosystem services are increasingly embedded in global and national environmental policies, geodiversity and the services derived from these abiotic features have not received the same status and standing as their biotic counterparts (e.g. Crofts, 2014; Gray, 2018; Schrodt et al., 2019; van Ree et al., 2017). In fact, 'nature' is often used in literature as a synonym for biodiversity alone, excluding the physical environment composed by abiotic nature (Gray, 2013, 2018). Thus, as a parallel to (Gray, 2011, 2013, Gray, 2018), or as a complement to (van Ree and van Beukering, 2016; van Ree et al., 2017) the ecosystem services concept, the concept of geosystem services has been suggested as a way for making the full values of geodiversity (Gray, 2011, 2013, Gray, 2018) and the subsurface (van Ree and van Beukering, 2016; van Ree et al., 2017) visible and acknowledged, supporting integrated decision-making in spatial planning and environmental policy making. As with ecosystem services, geosystem services have been categorised into provisioning, regulating, cultural and supporting services, in addition to the novel knowledge services category (Gray, 2011, 2012, 2018). The ecosystem services concept has brought attention to the living part of ecosystems and is operationalised to support well-informed decisions with respect to present and future values. The concept of geosystem services has the potential to improve the understanding and raise awareness of the multifunctionality of the subsurface, and to serve as basis for consideration and inclusion of diverse subsurface aspects in spatial planning processes (Norrman et al., 2021; van Ree et al., 2017).

However, despite geosystem services being discussed in scientific literature during the last decade from various perspectives, it is not yet defined in a unified way in scientific literature. It should be emphasized that while the term *geosystem* has been discussed for at least 60 years by physical geographers and landscape ecologists in Eastern European (particularly Russian and Eastern German) literature, the geosystem services concept is only distantly related., Sochava (1963, 1974, 1975, 1978) introduced the *geosystem* conceptualisation in 1963 as a geographical approach to understanding landscapes as being comprised of a series of interacting dynamic nested geosystems of different spatial dimensions which are hierarchically organised. However, possibly as the initial papers that defined and described this perspective on geosystems were published in Russian or German, and only actually translated some decades later into English, these ideas did not broadly transfer into the international scientific discourse (Bastian et al., 2015). However, Frolova (2019) accentuates that these ideas were at least, to some extent, adapted into Western European landscape-related scientific schools (e.g. Christopherson and Birkeland, 2018). With the increasing popularity of the ES framework, which in part addresses the same aspects — material goods, different forms of utilisation and socio-economic and environmental functions of the landscape – the *geosystem*[2] conceptualisation has gained growing attention as a possible approach to improve the assessment of ecosystems and their services (e.g. Bastian et al., 2015).

The overall aim of this study was to review current definitions of geosystem services and their categorisation, and to suggest how the concept of geosystem services can support a more holistic subsurface planning process. Specific objectives were to: (i) review definitions and conceptualisations of geosystem services, (ii) identify geosystem services listed in literature and compare these with the CICES V5.1 abiotic extension, and (iii) demonstrate uses and benefits of each identified geosystem service and relate it to subsurface planning.

[1] Boundary objects are concepts that are elastic enough to be adapted to different contexts and discourses but contain enough immutable content to function as a channel of communication between these different positions (Star and Griesemer, 1989).

[2] It should be noted that the terms geosystem and geosystem services are also used in conjunction with satellite position technologies - but in this context, these terms refer to providing functionality in geo-positioning networks.

Table 1
Important terms used in this paper and their respective definitions in literature, listed in alphabetical order.

Term or concept	Definition or interpretation
Atmosphere	Atmosphere is defined as "the gas and aerosol envelope that extends from the ocean, land, and ice-covered surface of a planet outward into space" (Pielke, 2020).
Biodiversity	Biodiversity (or biological diversity) refers to the variety of living species on Earth – including the diversity within species, between species and of ecosystems (Tansley, 1935). This definition is also used in the Convention on Biological Diversity.
Biosphere	The biosphere is a global ecosystem composed of living organisms (biota) and the abiotic (non-living) factors from which they derive energy and nutrients. The abiotic portion of each ecosystem in the biosphere includes the flow of energy, nutrients, water, and gases and the concentrations of organic and inorganic substances in the environment (Gates et al., 2020).
Ecosystem	An ecosystem is widely defined as the community of fauna and flora together with the abiotic environment in which they reside (MA, 2005).
Ecosystem services (ES)	Ecosystem services are "the contributions that ecosystems make to human well-being, and distinct from the goods and benefits that people subsequently derive from them" (Haines-Young and Potschin-Young, 2018). Three widely accepted classification systems for ecosystem services have emerged in recent years: the Millennium Ecosystem Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (Sukhdev et al., 2010) and the Common International Classification of Ecosystem Services (Haines-Young and Potschin-Young, 2018).
Geodiversity	The most commonly used definition of geodiversity (Boothroyd and McHenry, 2019, concluded that 88 % of the scientific articles in their literature study used this definition or variants of it) is supplied by Gray as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes" (Gray (2013, p. 12). Geodiversity is analogous to biodiversity and was initially introduced by Sharples (1993) and Wiedenbein (1993) in 1993, shortly after the Convention on Biological Diversity was agreed upon at the Rio Earth Summit in 1992 (Gray, 2018).
Geosystems	Sochava, 1974, p.4) defined a geosystem, regardless of its spatial dimension, as the interrelated components of the natural environment that comprise one unified whole and adhere to regularities within the geographic envelope or across landscapes[*)]. These components are both biotic and abiotic (Sochava, 1974, p.50; 1978, p.20).
Hydrosphere	The hydrosphere is defined by Britannica (2020a) as the "discontinuous layer of water at or near the planet's surface; it includes all liquid and frozen surface waters, groundwater held in soil and rock, and atmospheric water vapour".
Lithosphere	The lithosphere is defined by Britannica (2020b) as the "rigid, rocky outer layer of the Earth, consisting of the crust and the solid outermost layer of the upper mantle. It extends to a depth of about 60 miles (100 km)".
Natural capital	Natural capital can be defined as the (global) stock of biotic and abiotic resources i.e. the combined resources of the lithosphere (including the pedosphere), the atmosphere, the hydrosphere and the biosphere, that enhance the welfare of human society (e.g. Brilha et al., 2018; Costanza et al., 1997; Smith et al., 2017, World Forum, 2017).
Pedosphere	The pedosphere is defined by Merriam-Webster as the upper part of the Earth's crust that contains the soil layer (Merriam-Webster, n.d.) i.e. the loose part of the lithosphere.
Surface, subsurface, suprasurface	The subsurface is all materials and geological formations below the earth's rigid surface i.e. it stretches from the earth's rigid surface to its centre (Norrman et al., 2021). The surface is the earth's surface on the top of the land or sea. Suprasurface extends from the surface upwards i.e. the atmosphere.

[*)] Authors' own translation from original text in Russian.

Table 1 provides a list of terms and concepts and their corresponding definitions or interpretations as used in this paper.

2. Materials and methods

A systematic literature review of existing research using the search term "geosystem services" in the Scopus database, following the Preferred Reporting Items for Systematic Reviews and meta-Analyses (PRISMA) guidelines (Moher et al., 2009), was carried out as an initial step. The PRISMA protocol was slightly altered in this study as some of the steps were not applicable (e.g., sensitivity analyses and certainty assessments), and to accommodate that the study selection and data extraction were carried out by a single researcher instead of two independent researchers.

The aim of the systematic review was to identify articles in which a definition of geosystem services was given, or could be inferred from, or in which examples of geosystem services were provided. Articles which met one (or both) of these two criteria were considered eligible for this study. Emphasis was placed on journal articles that were geared towards geosystem services or abiotic services, published in primarily geoscientific, geoconservation or ecosystem services literature. Only peer reviewed texts in English were included. The three key activities of the systematic review were: 1) identify and collect relevant research (mapping of research field), 2) critically appraise the research articles in a systematic manner, and 3) combine the findings into a coherent statement (a synthesis of geosystem services).

The following search strings were applied to the Scopus database: "geosystem", "geodiversity", and "abiotic services". The broader search terms "geodiversity" and "abiotic services" were used to capture geosystem services and associated benefits that are discussed outside of the geosystem services' terminology. In the first sorting, based on titles and abstracts, 26 duplicates and 23 records without author(s), such as texts related to errata, corrigenda or summaries of conferences, were removed. After screening the title, abstract and keywords of the remaining 2609 records, 2472 irrelevant posts (i.e. items that contained the search terms but neither addressed geosystem services or abiotic services nor yielded a definition of these services that could be inferred) were removed manually. The full texts of the remaining 137 records were carefully assessed for relevance, after which 109 records were excluded. These texts were removed because they i) focused on a particular site with no reference to geosystem services or abiotic services as a concept, ii) focused on improving remote sensing techniques, or iii) had a rigid focus on geoheritage or geoconservation with no reference to geosystem services. In total, 29 records (Appendix A, Table A1) matched the eligibility criteria and were thus included in the synthesis (Fig. 1).

After the initial step of identifying relevant publications, examples of geosystem services and their categorisation in the aforementioned literature were identified. The list of geosystems services was then sorted according to whether these services were included or missing from the abiotic extension of the well-established CICES V5.1 framework (Haines-Young and Potschin-Young, 2018). Examples of associated benefits of geosystem services were either identified from literature or suggested by the authors. Finally, geosystem services that are relevant to subsurface planning in a broader context were identified.

3. Results

3.1. Definitions of geosystem services

Throughout the reviewed literature, the term "geosystem services" is used in a different context to that of the *geosystem* concept suggested by Sochava in the 1960 s and the emerging picture of the concept is both one of novelty, with all the reviewed records published within the last decade (Appendix A), and one currently showing inconsistency. Different authors have emphasised different aspects and have envisaged different approaches to connecting abiotic services to the ecosystem

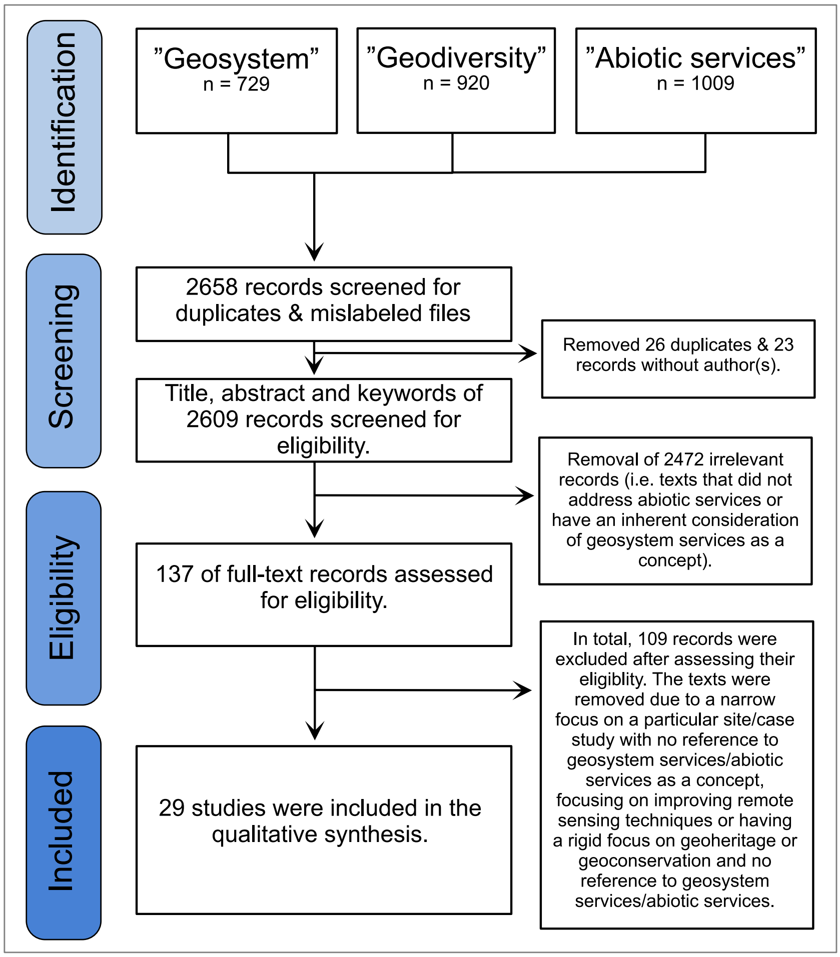

Fig. 1. PRISMA flow diagram and overview of search strings applied to the SCOPUS database for the literature review and the corresponding search results.

services framework (e.g. the use of the rather contradictory term abiotic ecosystem services). This inconsistency is further emphasised by semantics as the term geosystem is recognised in different disciplines and embodies different elements.

There are two prominent definitions of geosystem services in the reviewed recent literature: geosystem services as underpinned by geodiversity (definition A), and geosystem services as related to services from the subsurface (definition B). What geosystem services constitute and the difference between the two definitions are described below.

A. Fox et al. (2020), referring to Gray (2011), defined geosystem services as “all services associated with geodiversity independent of interactions with biotic nature” (Fox et al., 2020, p. 152). In this definition, geodiversity underpins and specifies the basis for the flow of services stemming from both the biotic and abiotic features of the ecosystem (Alahuhta et al., 2018; Gordon and Barron, 2013; Gordon et al., 2012; Gray et al., 2013). As described in the syntheses by Boothroyd and McHenry (2019), early definitions of geodiversity were synthesised and later redefined by Gray (2013, p. 12) as “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes”.
B. van Ree and van Beukering (2016) and van Ree et al. (2017) defined geosystem services as “the goods and services that contribute to human well-being specifically resulting from the subsurface” (van Ree and van Beukering, 2016, p. 34). The authors formulated a distinction between the stocks (e.g. mineral resources, stability) and the flows of services (associated with geological, energy and material cycles) stemming from these stocks. The geosystem services were differentiated from ecosystem services by van Ree and van Beukering (2016) as the geosystem services originate from the deep-seated stocks, rather than from the critical zone where most of the biotic activity takes place. The boundary is delineated by the strong decline in biological activity, located in the pedosphere, which forms a transition zone between the two types of services (van Ree et al., 2017).

3.2. *Geosystem services and their relation to ecosystem services*

The difference between the two identified definitions of geosystem services is not only (geo-)spatial but also, in part, reflects a different approach to the interactions between abiotic and biotic components. This difference can be illustrated through the different usage of the term geosystem services by Gray (2011, 2018) and van Ree and van Beukering (2016). Gray (2011, 2018) referred to geosystem services as the wide range of abiotic services that are the direct result of the planet’s geodiversity, independent of the interactions with biotic nature – in this sense, geosystem services constitute only the abiotic parts of the environment but there is no differentiation of suprasurface and subsurface features. This is in contrast to van Ree and van Beukering (2016) who used the term geosystem services to delineate the natural capital and services related to the subsurface. The subsurface is generally associated with low biological activity, due to the lack of sunlight and often anaerobic conditions, however, it still hosts microorganisms that are beneficial to human society and are thus included in van Rees’s definition of geosystem services (van Ree et al., 2017).

Fig. 2 shows graphical interpretations of the two suggested

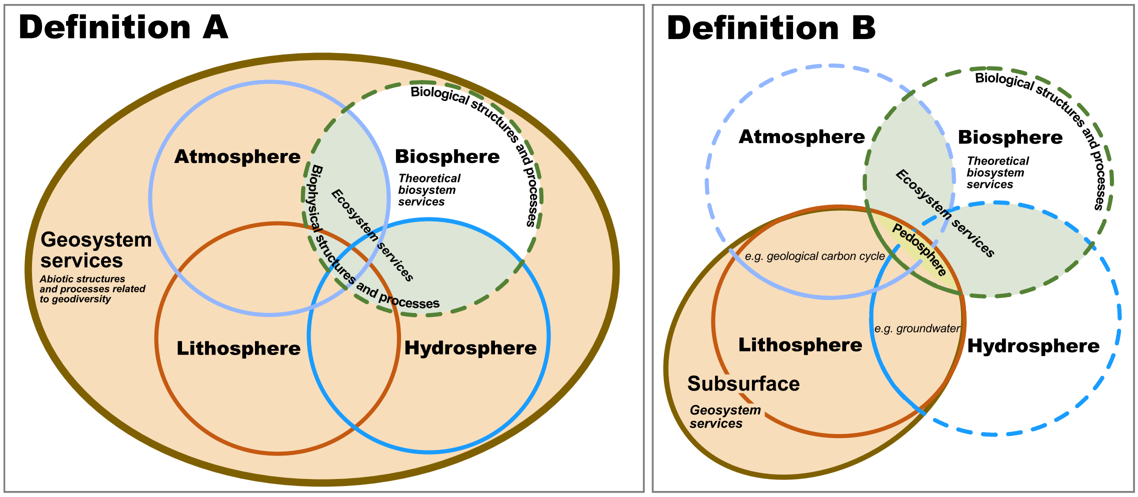

Fig. 2. Graphical interpretations of definitions A and B of geosystem services (shaded brown area) in relation to ecosystem services (shaded green area). The brown shaded areas represent the parts of nature that give rise to geosystem services according to the two definitions. Spheres, or parts of spheres, which do not include geosystem services are dashed. In definition A, ecosystem services are separated from geosystem services as the former services require interactions with biotic nature to be delivered and maintained, while still emphasizing that some ecosystem services are primarily driven by abiotic functions. In definition B, the pedosphere in the uppermost part of the lithosphere acts as transition zone from (surface) ecosystem services to (subsurface) geosystem services. The graphical representation of ecosystem services is based on Fox et al. (2020) in both definitions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

definitions of geosystem services, that is, how they relate to ecosystem services and how these conceptualisations of geosystem services capture nature's abiotic services. In definition A, geosystem services arise from all abiotic parts of nature underpinned by geodiversity, where geodiversity is the natural range of geological, geomorphological, soil and hydrological features. Definition B does not relate to the geodiversity concept at all. Instead, only those parts of nature that belong to the subsurface give rise to geosystem services, with a transient zone downwards in the pedosphere from providing fewer to more geosystem services and more to fewer ecosystem services. Ecosystem services (represented by green colour in the graphical interpretations, Fig. 2) arise from biophysical structures and processes, created by the intricate interaction of biotic and abiotic nature (shown in Fig. 2 as the overlap of the different spheres). While services stemming exclusively from the biological components of nature are theoretically plausible (included in the Fig. 2), Fox et al. (2020) concluded that it is difficult to provide realised examples in nature. In definition A, ecosystem services are underpinned by abiotic features and processes but are distinctly separated from geosystem services as ecosystem services require interactions with biotic nature to be delivered and maintained, whereas, in definition B, there is a slight overlap relating to biological processes occurring in the deeper subsurface, e.g. chemical processes mediated by microorganisms (i.e. biochemical processes). Although van Ree and van Beukering (2016) explicitly points to atmospheric services as separate from geosystem services, they also state that "At a larger scale long term geochemical cycles are important components of the geosystem in which carbon sequestration and the potential impacts of carbon capture storage (CCS) as climate change abatement technology are relevant to ecosystem functioning" (van Ree and van Beukering, 2016; pp 34). For this geochemical cycle to take place, there must be some sort of interaction between the atmosphere and the lithosphere; therefore, the suggested overlap in the graphical interpretation of definition B (Fig. 2). The overlap of the hydrosphere, lithosphere, biosphere, and atmosphere in definition B is derived based on similar reasoning.

3.3. Identified geosystem services, categorisation and comparison with CICES' abiotic extension

Table 2 summarises all identified examples of geosystem services from the reviewed literature, categorised into "regulating", "supporting", "provisioning" and "cultural" services. Gray (2011) additionally included "knowledge" services separately, but which are formally recognised as part of cultural services in the Millennium Ecosystem Assessment (MA, 2005). The examples of geosystem services from the reviewed literature have been sorted according to whether they were included in or missing from the abiotic extension of CICES V5.1, to capture which of these services are already addressed in the ecosystem services framework. Interpretations of the listed geosystem services in reviewed literature are given, showing their uses and corresponding benefits. Finally, the spatial origin of the geosystem services is noted. The two views (definitions A and B) of what the geosystem services concept constitutes have resulted in different abiotic aspects being used to typify geosystem services. Some of these examples are shared by both definitions whilst others conflict. The former applies particularly for most of the provisioning and knowledge services, which both definitions acknowledge. However, in the regulating and supporting services categories, the two views provide different examples of geosystem services and, thus, differ on what it is the geosystem services concept addresses.

The supporting services category is controversial in ecosystem services frameworks as these services may pose a risk of double counting when they serve as inputs to other ecosystem services, i.e. they are intermediate ecosystem services in the provision of final ecosystem services (Jax, 2016; Potschin and Haines-Young, 2016; Rives et al., 2016). One solution to minimise this risk is to exclude supporting services from classification, as is done in CICES for ecosystem services. The supporting services category is however included in both definitions of geosystem services. Some supporting geosystem services are related to carrier functions of the geological substrate, which is used directly by humans to provide services relating to well-being. Hence, there is low risk of double counting. The carrier concept has been included in the classification of ecosystem services since the 1970 s, when it was referred to as functions of the natural environment for society (Braat et al. (1979) cited in van der Meulen et al., 2016a). Carrier functions were also recognised in the more recent ecosystem services classification framework by de Groot (1992, 2006). The authors (Braat et al., 1979; de Groot, 1992, 2006) specified the importance of the geological substrate as it provides services to humans e.g. a medium for construction (supporting), extraction of minerals and other materials (provisioning), and

Table 2
Resulting list of geosystem services found in the reviewed literature, categorised into Regulating, Supporting, Provisioning and Cultural services. Interpretations are made of the listed geosystem services in literature in order to list example of uses and associated benefits, and the spatial origin of the geosystem services. Definition A: all services associated with geodiversity independent of interactions with biotic nature. Definition B: the goods and services that contribute to human well-being specifically resulting from the subsurface.

Category	Geosystem Service		Definition	Interpretation		
	Included in the abiotic extension of CICES V5.1			Example of uses	Associated benefit(s)	Spatial origin
	Yes (CICES code)	No				
Regulating services	Regulation of surface water quality (lakes, reservoirs etc.) by dilution (5.1.1.1)		A	Use of freshwater/marine systems as a pollution sink	Disposal of waste, reduction in costs for handling waste	Surface - subsurface
	Regulation of oceanic chemistry (5.1.1.3)		A	Use of e.g. calcium carbonate dissolved in terrestrial flowing water to buffer the oceanic pH	Reduction in loss of biotopes and biodiversity	Surface - subsurface
	Regulation of erosion (5.2.1.1)		A	Use of e.g. passive erosion protection systems	Reduction in damage costs	Surface - subsurface
	Regulation of mass movements (5.2.1.1)		A	Regulation of groundwater levels to prevent landslides	Reduction in damage costs and providing a safer environment	Surface - subsurface
	Regulation of baseline and extreme events, flow of water (5.2.1.1 & 5.2.1.2)		A	Use of e.g. natural levees to protect from flooding	Reduction in damage costs and providing a safer environment	Surface - subsurface
	Regulation of water quantity through porous media (5.2.1.2)		A, B	Use of porous media such as sand and gravel to infiltrate, store and transport water	Reduction of flooding and associated damage costs in cities by allowing storm water to infiltrate	Subsurface
	Regulation of water quality through filtration (5.1.1.3)		A, B	Use of porous media to filtrate pollution, bacteria and other nuisances from groundwater	Reduction in treatment costs. Increased environmental quality	Subsurface
	Regulation of limnological chemistry (5.1.1.1)		A	Use of e.g. calcium carbonate dissolved in (flowing) water to buffer pH in limnological systems	Reduction in loss of biotopes and biodiversity	Surface - subsurface
	Regulation of the hydrological cycle (5.2.1.3 & 5.2.2.1)		A	Regulation by e.g. topographical elevation to channel or block the passage of rain-producing weather systems (rain shadow)	Providing a stable (local) climate	Suprasurface - surface - subsurface
	Regulation of atmospheric chemistry (5.1.1.2)		A, B	Use of e.g. abiotic carbon sequestration (CSS) to regulate atmospheric greenhouse gases	Reduction in predicted damage cost of climate change impacts	Suprasurface - surface - subsurface
		Regulation by the thermal buffer capacity of the subsurface	B	Use of the subsurface as a heat exchanger (e.g. for shallow geothermal energy systems)	Reduced heating and/or cooling costs	Subsurface
	Regulation of soil and bedrock chemistry (5.2.2.1)		A, B	Use of the subsurface and associated (bio)geochemical processes to buffer pH in soils and bedrock	Reduction in loss of biotopes and biodiversity	Surface - subsurface

Category	Geosystem Service		Definition	Interpretation		
	Included in the abiotic extension of CICES V5.1			Example of uses	Associated benefit(s)	Spatial origin
	Yes (CICES code)	No				
Supporting services		Retention of water in soils	A	Use of soil cavities to retain water in soil, which in turn is used by plants and other organisms	Contributing to plant productivity and soil health	Surface - subsurface
		Soil development	A	Use of weathering products to add nutrients to the soil	Contributing to soil renovation, increasing plant productivity	Subsurface
		Retention of nutrients in soils	A	Use of the soil ability to retain nutrients	Contributing to soil fertility and soil health	Subsurface
		Habitat provision (marshes, caves, beaches etc.)[1]	A,B	Use of the natural environment by an organism adapted to surviving in that environment	Contributing to a diverse landscape and to biodiversity	Surface - subsurface
		Stable platform to build on and within	A, B	Use of the (sub) surface to build on	Contributing to a platform to build on and within	Subsurface
		Space (for construction and infrastructure)	A, B	Use of the (sub) surface for space	Relieves the increasingly congested surface. Can provide protection for sensitive activities.	Subsurface
		Disposal and storage	A, B	Use of the subsurface to bury and store waste or materials underground	Natural formations can provide good storage space without expensive construction for e.g. water and carbon dioxide. Waste has commonly been buried, for example, to prevent e.g. spreading of dust, smell, radiation etc.	Subsurface

Category	Geosystem Service – Included in the abiotic extension of CICES V5.1 – Yes (CICES code)	No	Definition	Interpretation – Example of uses	Associated benefit(s)	Spatial origin
Provisioning services	Surface water resources for drinking (4.2.1.1)		A	Use in public water supply systems	Access to clean drinking water	Surface
	Groundwater resources for drinking (4.2.2.2)		A, B	Use in public water supply systems, mineral water	Access to clean drinking water that requires little treatment	Subsurface
	Surface water energy resources (4.2.2.2 & 5.2.1.3)		A	Use of freshwater as an energy source	Renewable energy source	Surface
	Surface water used as a material (non-drinking purposes) (4.2.1.2)		A	Use of surface water for e.g. cooling purposes or for irrigation	Reduces energy costs. Reduced material costs	Surface
	Groundwater used as a material (non-drinking purposes) (4.2.2.2)		A, B	Use of groundwater for e.g. irrigation or as a component in industrial processes. Recharge of lakes, rivers, and wetlands.	Reduces energy costs. Reduced material costs	Subsurface
	Industrial minerals (4.3.1.2)		A, B	Use of minerals, such as graphite by industry, based on their physical and/or chemical properties	Access to these minerals	Subsurface
	Minerals for nutritional purposes (4.3.1.1)		A, B	Use of minerals, such as salt, for nutrition	Access to these minerals	Subsurface
	Non-renewable energy resources (4.3.1.3)		A, B	Use of oil, natural gas, uranium resources etc. to provide energy	Energy sources	Subsurface
	Geothermal resources (4.3.2.5)		A, B	Use of groundwater to heat or cool buildings	Reduced heating and/or cooling costs. Renewable energy source	Subsurface
	Construction materials (e.g. rock aggregates, sand and gravel) (4.3.1.2)		A, B	Use of materials, minerals and rock for construction works	Access to these construction materials	Subsurface
	Ferrous ores, Base metals, Precious metals and Rare Earth Elements (REEs) (4.3.1.2)		A, B	Use of metallic minerals, such as copper and lithium, for industrial purposes	Access to these minerals	Subsurface
	Ornamental resources (4.3.1.2)		A, B	Use of mineral and/or rocks, such as metals, gemstones and marble, for ornamental purposes	Access to these ornamental resources	Subsurface

Category	Geosystem Service – Included in the abiotic extension of CICES V5.1 – Yes (CICES code)	No	Definition	Interpretation – Example of uses	Associated benefit (s)	Spatial origin
Cultural services	Iconic sites (e.g. for cave exploration) (6.1.1.1)		A, B	Use of caves for exploration	Tourism	Surface - subsurface
	Recreational sites (e.g. rock-climbing sites and trail-running tracks) (6.1.2.1)		A	Use of rock faces for climbing, tracks to run on etc.	Recreation and tourism	Surface - subsurface
	Aesthetic landscapes (6.2.2.1)		A, B	Viewpoints for iconic mountain peaks, undulating landscapes etc.	Tourism and recreation	Surface - subsurface
	Sacred and historical sites (6.2.1.1)		A, B	Use of sacred and historical sites to understand our history	Tourism and scientific endeavours	Surface - subsurface
Knowledge services, formally part of Cultural services in the MA classification.	History and evolution of the Earth (6.1.2.1)		A, B	Use of distinctive geological, geomorphological or mineralogical sites to understand the history of Earth	Tourism and scientific endeavours	Surface - subsurface
	History and evolution of life (6.1.2.1)		A, B	Use of fossils to understand the history of life on Earth	Tourism and scientific endeavours	Surface - subsurface
	Paleoclimates and paleoenvironments (6.1.2.1)		A, B	Use of paleoclimate for environmental monitoring and forecasting	Scientific endeavours	Surface - subsurface
	Educational resource (6.1.2.1)		A, B	Use of geological and geomorphological features for educational purposes (e.g. sites for field trips)	Scientific endeavours and educational resources	Surface - subsurface

[1]Habitat provision as a service is not included in the abiotic extension of CICES. However, it is included in CICES as a biotic service under Regulation and Maintenance (CICES code 2.2.2.3).

energy and waste storage (regulating). These services were, however, excluded from the later studies by de Groot et al. (2012) and focus shifted to the biotic part of nature.

3.4. Geosystem services to support subsurface planning

A classical view of subsurface planning – also referred to as planning of urban underground space (UUS) – relates to designing and localising underground construction (Volchko et al., 2020). In recent years, the subsurface has been recognised as a multifunctional natural resource. A more holistic view of subsurface planning suggests that these multiple subsurface aspects should be taken into consideration in spatial planning processes, as well as facilitating the prioritising of subsurface resource usage and better accounting of the subsurface in surface plans (e.g., Admiraal and Cornaro, 2016; Bobylev, 2018; de Mulder et al., 2012; Hooimeijer and Maring, 2018; Parriaux et al., 2004; van Ree et al., 2017;

Table 3
Selection of geosystem services identified in literature that are relevant to subsurface planning in a broader context than only applications for urban underground space, with examples of relevance.

Category	Geosystem services	Examples of relevance to subsurface planning
	(included as geosystem service in definition A and/or B)	
Regulating services	Regulation of erosion (A)	Changes to the subsurface, including the surface by e.g. excavation, can alter the rate and distribution of surficial erosional processes. Consideration of this geosystem service in the planning process can result in reduced costs of erosion control.
	Regulation of mass movements (A)	Changes to subsurface conditions by e.g. excavation, deep foundation installation, drainage or other construction activities can cause or prevent mass movements, such as landslides and rock falls. Lack of consideration of this geosystem service can result in high damage cost and risks to life and limb.
	Regulation of water quantity through porous media (A, B)	Changes to the subsurface can alter the ability of the subsurface to infiltrate, store and regulate e.g. groundwater recharge and urban runoff. This is a beneficial service that is becoming more important in urban areas where impervious surfaces are often constructed during land development. Groundwater resources may also recharge wetlands and other surface water bodies, providing important contributions to the ecosystems in receiving waters. Preventing the loss of this geosystem service in the planning process can result in reduced costs for soil subsidence and costs for restoring groundwater levels by artificial infiltration.
	Regulation of water quality through filtration (A, B)	Generally, as shallow groundwater moves throughout the subsurface, harmful compounds and organisms are adsorbed to the porous media, increasing water quality. Depending on the geological setting, the type of porous media or rock, and the redox-conditions, dissolution of minerals can cause leaching of metals or acid water and cause problems related to human health, ecosystems or constructions. Preservation of this geosystem service in planning, as well as proper planning of possible unwanted disturbance to groundwater systems is of vital importance, both if groundwater is assumed to be used for supply of drinking water and to avoid damage costs.
	Regulation by the thermal buffer capacity of the subsurface (B)	The ability of the subsurface to act as a heat exchanger is widely used as a heating and cooling source for households and building complexes. Heating excess can be stored in the subsurface for future use. Energy wells should be considered in planning to avoid potential conflicts with other subsurface constructions such as tunnels.
	Regulation of soil and bedrock chemistry (A, B)	This subsurface function relates to ensuring a safe environment for both humans and ecosystems by addressing both anthropogenic and natural contamination, including areas with high background radiation from naturally occurring radon. As such, it is relevant for planning, and illustrates the importance of considering the subsurface conditions in planning processes.
Supporting services	Stable platform to build on and within (A, B)	The subsurface provides ground to build on and within where the geological conditions dictate the stability of both surface and subsurface constructions. Consideration of the natural preconditions in the early planning process can result in reduced costs of foundations and tunnelling.
	Space (e.g. for living, infrastructure, cables and pipelines) (A, B)	Subsurface space can be used to relieve the crowded surface, to hide infrastructure and/or protect critical buildings and infrastructure from weather or malicious acts. Proper planning of the use of underground space provides opportunities to create a safer environment, preserve amenities above ground and avoid conflicting claims on space.
	Disposal and storage (A, B)	The subsurface can be used for short-term and long-term storage, both in constructed space but also in natural formations. It has traditionally been used for storage purposes e.g. caverns for freshwater, hot water, oil, gas. Furthermore, the subsurface can be used for disposal purposes e.g. for waste including municipal landfills. Several concepts have been suggested for the subsurface to act as a repository of more hazardous and radioactive waste. More recently, advances in storing carbon dioxide in natural formations have come to the fore due to the global climate crisis, along with various forms of energy storage (hydrogen and methane gas, and compressed air). Areas with appropriate properties for storage of various substances in natural formations need to be carefully managed.
	Habitat provision (A, B)	The subsurface provide habitats for wide variety of species; burrowing animals such as rabbits, badgers, worms rely on the soil and sub-soil for their living quarters, other animals such as some bats and salamanders make their home in caves, and the deep subsurface hosts plenty of stygofauna and troglofaunal. Areas with sensitive or endangered species or having high biodiversity needs to be carefully managed so as not to compromise their continued existence.
Provisioning services	Groundwater resources for drinking (A, B)	Aquifers, the underground layers of water-bearing permeable rock, rock fractures or unconsolidated materials host vital groundwater resources that are used for drinking purposes. Valuable aquifers need to be properly accounted for in the planning process to protect water resources, both in terms of quality and quantity. Future activities and construction should be planned so as not to compromise beneficial use of groundwater resources.
	Groundwater used as a material (non-drinking purposes) (A, B)	Groundwater resources are also used for extraction for industrial purposes and need to be properly protected, thus accounted for in the planning processes.
	Industrial minerals (A, B)	The subsurface hosts valuable industrial minerals used in a variety of applications. Availability should be specified in plans, and future developments should be planned so as not to compromise current or future use of these resources.
	Minerals for nutritional purposes (A, B)	The subsurface hosts valuable nutritional minerals (e.g. salt). Availability should be specified in plans, and future developments should be planned so as not to compromise current or future use of these resources.

(*continued on next page*)

Table 3 (*continued*)

Category	Geosystem services	Examples of relevance to subsurface planning
	Non-renewable energy resources (A, B)	The subsurface hosts valuable non-renewable energy resources e.g. coal, oil and uranium[1)]. Availability should be specified in plans, and future developments should be planned so as not to compromise current or future use of these resources.
	Geothermal resources (A, B)	The subsurface hosts geothermal resources at various depth around the world. This is a resource that can be used to heat and/or cool buildings and industrial complexes, and potentially be connected to district heating systems. If properly planned, the costs for heating and cooling can be reduced over the long term. Proper planning can ensure replenishment of the ground thermal field and prevent depletion of this geosystem service through extreme extraction rates.
	Construction materials (e.g. sand, gravel, rock material) (A, B)	The subsurface hosts valuable construction materials that are used for construction purposes. Proper planning for the use of excess material in the construction process may reduce the costs for disposal and backfilling at other construction sites. Extraction of sand and gravel may also be in conflict with the protection of groundwater resources and needs to be properly managed.
	Ferrous ores, Base metals, Precious metals and Rare Earth Elements (REEs) (A, B)	The subsurface hosts valuable base and rare metals that are used in a variety of applications. Availability should be specified in plans, and future developments should be planned so as not to compromise current or future use of these resources.
	Ornamental resources (e.g. marble) (A, B)	The subsurface hosts valuable ornamental resources that are used to decorate e.g. houses. Availability should be specified in plans, and future developments should be planned so as not to compromise current or future use of these resources.
Cultural services	Iconic sites (e.g. caves for exploration and tourism) (A)	The subsurface hosts iconic sites that can be of importance to business areas such as tourism. This service can be accounted for in the planning process.
	Sacred and historical sites (A, B)	The subsurface hosts sacred and historical sites that are of archaeological or heritage interest. This service can be accounted for in the planning process.
Knowledge services, formally part of Cultural services in the MA classification.	History and evolution of the Earth (A)	The subsurface hosts sites that are of national or international scientific importance, containing evidence or findings related to e.g. the history and evolution of the Earth. These sites may need to be accounted for in the planning process and preserved for scientific research and educational purposes.
	History and evolution of life (A)	The subsurface hosts sites that are of national or international scientific importance, containing evidence or findings related to e.g. the history and evolution of life. These sites may need to be accounted for in the planning process and preserved for scientific research and educational purposes.
	Paleoclimates and paleoenvironments (A)	The subsurface hosts sites that are of national or international scientific importance, containing evidence or findings related to e.g. paleoclimates and paleoenvironments, that can be used, for example, to build climate models. These sites may need to be accounted for in the planning process and preserved for scientific research and educational purposes.
	Educational resource (A)	The subsurface hosts sites that are educational resources that can be used by students during field trips. Important educational sites may need to be accounted for in the planning process and preserved for the future in order to educate future Earth science students.

[1)] Peat could potentially be regarded as a geosystem service due to the time perspective i.e. the long time it takes for peat to develop.

Volchko et al., 2020). Table 3 lists selected geosystem services that are considered relevant for subsurface planning in the broader sense.

Norrman et al. (2021) made a systematic inventory of subsurface qualities to map various potential conflicts in an area in the City of Göteborg, in Southwest Sweden. The concept of subsurface qualities originates from the Netherlands (Ruimtexmilieu, 2021; Hooimeijer and Maring, 2018) and, even though these qualities are categorised in the same four categories as ecosystem services and geosystem services, it does not differentiate between biotic and abiotic qualities, simply stating that these are relevant in planning and urban transformations. The entirety of suggested subsurface qualities relating to abiotic features can be found in Table 3, however with a somewhat different grouping.

4. Discussion

4.1. Geosystem services – Part of the ecosystem services framework?

What authors mean when they refer to, write about, or discuss geosystem services depends on to whom and what issue the authors are addressing. The literature review revealed that there are two definitions of geosystem services which differ in terms of delineation (Fig. 2): the first one captures all of nature's abiotic services to humankind, the second one brings to the fore services stemming from the subsurface. It is clear that, in the reviewed literature, the term geosystem service is used in a different context compared to the *geosystem* concept suggested by Sochava in 1960 s and instead, geosystem services have generally been used as an abiotic analogue for ecosystem services.

In the early 1990 s, de Groot (1992) argued for adopting an integrated approach with a set of services defined at that time as "functions of nature". In Brilha et al. (2018), geosystem services are regarded as an integral part of ecosystem services, or rather as a part of the total natural capital, without distinguishing between geosystem services and ecosystem services. The authors concluded that most assessments of ecosystem services did not include "the full array of services associated with geodiversity" (Brilha et al., 2018, p. 22). Scholars also stress that services originating from abiotic systems, in particular from the subsurface (Authors van der Meulen et al. (2016a) and van Ree et al. (2017), and in general (Gray, 2018), are overlooked in ecosystem services frameworks. The findings outlined by Brilha et al. (2018), Gray (2018), van der Meulen et al. (2016a) and van Ree et al. (2017) are confirmed in this study: the seven supporting geosystem services are not included by definition and one of the regulating geosystem services is omitted in CICES abiotic extension (see Table 2). Brilha et al. (2018, p. 22) warned that "the current status of abiotic services within the ecosystem services approach is unsatisfactory, inconsistent and confusing, but if abiotic services are excluded, there must be a danger of a radical undervaluing of the contribution of all nature to human well-being". The recently created concept of Nature's Contribution to People (NCP) aims at a better understanding of the full value of nature (sensu Díaz et al., 2018) through widening the ecosystem services perspective towards a more cultural dimension of nature. However, NCP still does not seem to adequately include contributions of abiotic nature.

Perhaps it is not surprising that, although nature is comprised of both biotic and abiotic elements, the abiotic services that are not usually traded on a market, such as some of the supporting or regulating services, are often omitted or overlooked. Indeed, as Braat and de Groot

(2012) states, "The rationale behind the use of the ecosystem service concept was mainly to demonstrate how the disappearance of biodiversity directly affects ecosystem functions that underpin critical services for human well-being."(Braat and de Groot, 2012: pp 7). The ecosystem services concept is today firmly established in land and water management literature and practice. However, the emerging picture from the review is that a narrow focus on one part of nature (the biotic) fails to acknowledge other parts (abiotic), which is unsatisfactory for management of (all) natural capital. Fox et al. (2020) tries to acknowledge this in their suggested Geo-Eco Services Framework where ecosystem services are conceptualised as a result of biophysical structures and processes, and can be driven either mainly by biotic or geodiversity structures and processes. Similarly, Brilha et al. (2018) argued that geodiversity is an important part of the maintenance of ecosystem functioning and services. Indeed, it seems that areas with high geodiversity correlate well with high biodiversity (Schrodt et al., 2019 and references therein), but Alahuhta et al. (2020) state that more empirical evidence is required to establish the existence of robust geodiversity–biodiversity relationships. In response to these interactions between biotic and abiotic nature, the contemporary revision (V5.1) of the CICES framework (Haines-Young and Potschin-Young, 2018) includes an abiotic extension to capture some of these services for the sake of completeness. Our review of the geosystem services literature, however, suggests that this extension inadequately captures all abiotic services: 8 geosystem services are missing in CICES (Table 2).

Notwithstanding completeness, implementing abiotic services within a system which aspires to capture values of ecosystems and biodiversity can be complicated. This is illustrated by how geosystem services are delineated from ecosystems services in two ways, temporally and spatially, as suggested by van Ree and van Beukering (2016):

1. The origin and development of ecosystem services and geosystem services can, depending on the type of services, be differentiated by several orders of magnitude from the time perspective. This notion was discussed by, for example, both Chakraborty and Gray (2020) and van Ree and van Beukering (2016). These authors highlighted that referring to ecosystem services generally relates to features developed during modern times (i.e. hundreds up to thousands of years), whereas when geosystem services are referred to, these features can stem from present-day processes (e.g. groundwater recharge) back to features inherited from the past, sometimes traceable to the early evolution of the continental crust some 3 billion years ago. If both ecosystem services and geosystem services are to be managed within the same concept, the possible temporal difference between some of the services should be acknowledged.
2. Ecosystem services are similarly delineated from geosystem services spatially. Simplified, biotic ecosystem resources are typically derived from a considerably smaller range of depths compared to geosystem services. In the definition of geosystem services suggested by van Ree and van Beukering (2016), it is these two differences, the temporal and spatial, which constitute the distinction between ecosystem services and geosystem services, with the pedosphere acting as the transition zone between these two services.

For the sake of completeness, all of nature's services should ideally be considered in all environmental and natural resource management decisions, but whether abiotic services should be included in the ecosystem services framework can clearly be questioned. Nonetheless, there are examples indicating that abiotic services are already included in the ecosystem services framework in planning practices. In the municipality of Upplands-Väsby (20 km north of Stockholm, Sweden), the capacity of the soil for water infiltration and to retain water for flooding prevention is included in their inventory of ecosystem services (Ekologigruppen, 2015). In the recently developed tool EkoGeokalkyl (Carlsson et al., 2020), within an ecosystem services framework, the soil's capacity for infiltration of water is included as an important service for municipalities to account for in spatial planning. However, merging geosystem services into ecosystem services classification frameworks could potentially obscure and reduce the significance of the ecosystem services concept and, although the biotic services are intimately connected to the physical–chemical parts of nature (see e.g. Fox et al., 2020), there are, as outlined above, important differences, at least in relation to geosystem services. In addition, establishing a framework that considers all compartments of nature, and is still operative, may simply be too complex. Instead, it may be beneficial to delineate and establish, in literature and practice, geosystem services as a standalone complementary concept. Another approach is to assess contribution of each component of natural capital – i.e. lithosphere, pedosphere, hydrosphere, atmosphere, and biosphere – to human well-being separately using the methodological approaches developed over decades for ecosystem services. Building on strengths of the different disciplines, the integrated results of these individual assessments, with due care taken to interdependencies across the different spheres, could support well-founded decisions. Implemented well, this would provide consistency in the terminology across services and retain the benefits of a system approach, without diluting the more established ecosystem service concept. This could be beneficial in avoiding a similar issue faced by the geodiversity and geotourism terms raised by researchers such as Ollier (2012), who argued that geotourism on the verge of becoming so all-embracing to be rendered meaningless. In addition, it would address the inconsistency by which abiotic services are treated – where some authors have adopted the rather contradictory term abiotic ecosystem services (Gordon and Barron, 2011; Gordon et al., 2012; Gray, 2013; Hjort et al., (2015) whereas others have embraced geosystem services (e.g. Fox et al., 2020; Gray, 2011, 2018; van Ree and van Beukering, 2016; van Ree et al., 2017) or have abiotic services included in wider concepts, such as natural capital (e.g. Smith et al., 2017).

This review of literature related to geosystem services suggests that a unified definition could indeed be beneficial in communicating the importance of these services to decision-makers, policymakers, and the general public. However, it remains a non-trivial endeavour to unify and harmonise the geosystem services concept and terminology. As a suggestion to explore further, such an endeavour could mimic the CICES approach to ecosystem services, where the definition of each class of services consists of both an "ecological clause", describing the biophysical output, and a "use clause", describing the contribution to an eventual benefit. However, to make the definitions more operational, such structure ought to be complemented with tangible examples of specific geosystems services.

4.2. Geosystem services for improved subsurface planning

The importance of careful subsurface planning has already been highlighted by Webster some 100 years ago (Webster, 1914), and the point has been echoed by many scholars over the past 40 years, both in Sweden and internationally (e.g. Admiraal and Cornaro, 2016; Admiraal, 2009; Barker, 1991; Bobylev, 2009; de Mulder et al., 2012; Egerö et al., 1994; Evans et al., 2009; Hooimeijer and Maring, 2018; ITA, 2000; Jansson, 1976; Kaliampakos and Benardos, 2008; Makana et al., 2016; Norrman et al., 2016; Parriaux et al., 2004; SGU, 2017; Sterling et al., 2012; Volchko et al., 2020). National policies regarding subsurface planning have been developed in countries such as China and the Netherlands, and relevant legislation is enforced in Finland but, for most countries, such policies and laws are still lacking (for details on legalizations, polices and management approaches to subsurface resources, see de Mulder et al., 2012; Volchko et al., 2020). Inventories of spatial planning practices in European countries including Sweden (Mielby et al., 2017; Öberg and Sjöholm, 2019) reveal that a systematic approach to inclusion of the subsurface into spatial planning processes at a city-scale is, almost without exception, missing. In general, awareness of the subsurface, and the resources therein, typically only exists where either great opportunities or great risks are presented. In the more prevalent but less spectacular cases favourable subsurface conditions are often taken for granted (van der Meulen et al., 2016b).

The invisibility of the subsurface may compromise fair intergenerational and intragenerational distribution of subsurface resources as conflicting claims are common, either as conflicts between alternative subsurface uses, or conflicts between surface use and subsurface resources. Extraction of gravel from glaciofluvial deposits is often in conflict with its use as a drinking water supply, with or without artificial infiltration. One such example of many from Sweden, is the glaciofluvial delta formation Gråbodeltat adjacent to the lake Mjörn, and located in the Municipality of Lerum, Northeast of the City of Göteborg. At Gråbodeltat, extensive historical gravel extraction has negatively influenced the capacity of the deposit to act as a drinking water resource (Kretslopp och vatten, 2017). Another conflict related to the extraction of geomaterials is the topic of sterilization of resources, where economically valuable mineral resources are built upon preventing further exploration and extraction (Wrighton et al., 2014). However, it should be noted that if the potential gain is viewed as substantial enough, the extraction of minerals can be prioritized over preserving human settlements. The city of Kiruna and the town of Malmberget located in the uppermost northern part of Sweden situated on top of a large iron ore deposit mined by LKAB are such examples. With the start already set off in 2020, Malmberget will be moved and merged with the nearby town Gällivare, and the city of Kiruna will be moved approximately 3 km to allow further expansion and operation of the mines (https://samhallsomvandling.lkab.com/en/). In urban settings a common conflict is between the use of the subsurface for tunnelling and for installation of small private geothermal wells. These private geothermal wells can reach down 200 – 300 m and, if installed in the centres of dense cities, may conflict with future underground construction (Li et al., 2016). Another conflict is between urban surface plans that include dense exploitations and the creation of impervious surfaces which can reduce the retention of storm water and increase the risk of flooding. It may also impact the natural groundwater recharge which may cause lowering of pore pressures in soft soils, and in turn trigger soil subsidence (e.g. Bajni et al., 2019; Jaber, 2015).

For the purpose of subsurface planning, the concept of subsurface qualities (Ruimtexmilieu, 2021) includes both biotic and abiotic features of the subsurface. Although categorisation of the qualities is the same as in the ecosystem services and geosystem services frameworks, the concept of subsurface qualities does not refer to these. It also includes man-made features of the subsurface, which are not necessarily ecosystem or geosystem services but nevertheless important to consider in planning processes as an integral part of the subsurface, features such as cables, pipes, and underground structures. Hale et al. (2021) specifically referred to the urban underground space where the subsurface and its services interface with the built environment. Another related example is from the water protection field, where Gärtner et al. (2022) introduced the concept of water system services (WSS) along with a proposed list of WSS containing all biotic *and* abiotic services provided by a drinking water resource for the purpose of supporting decisions on implementing water protection measures. Both the concept of subsurface qualities (Ruimtexmilieu, 2021) and the suggested approach by Gärtner et al. (2022) have in common to support decisions in a specific field. Thus, these concepts and lists are developed for specific purposes and can as such easily be operative in those specific fields but may not necessarily be relevant in wider applications.

Although, at present, it is ecosystem services that are focussed on in planning, the subsurface with its abiotic parts also needs full consideration in planning. To move towards holistic subsurface planning, a basic knowledge of geoscience and the subsurface is required and needs to be broadly communicated. The concept of geosystem services has the potential to operate as a boundary object, similar to the ecosystem services concept (e.g. Hysing and Lidskog, 2021; Ainscough et al., 2019) and as such facilitating communication about the subsurface resources across different disciplines. Otherwise, in the more common but less spectacular cases, there is a risk that the essential services the subsurface provides are taken for granted, where the challenges associated with the subsurface are underestimated and referred to as unforeseen.

Both definitions A and B identified in literature can support subsurface planning as they list the same elements relevant to include. For the specific application of subsurface planning, definition B may be more easily communicated and understood as it has the subsurface as a clear focus. The concept of geosystem services has the potential to challenge the first-come-first-served principle to accessing the resources in the subsurface by: (1) providing a basis for a common understanding of the subsurface as a multifunctional resource, and (2) supporting an inventory of multiple subsurface potentials in the spatial planning processes through mapping of geosystem services – their identification, quantification and valuation – and identification of potential conflicts and synergies between them (Norrman et al., 2021; Volchko et al., 2020). Using a framework for geosystem services classification, multiple subsurface potentials can be systematically inventoried in a transparent way which is acceptable to all stakeholders. Such a framework can potentially support “a better integration of environmental sciences and cross disciplinary conversations” (Hale et al., 2021, p. 4198) and consequently avoid a development where the urban underground construction results in disruption to the geosystem and ecosystem services (Hale et al., 2021). An inventory may increase the understanding of the opportunities as well as the constraints or risks associated with the subsurface. The identified conflicting interests in the course of such an inventory can be made transparent and potentially also be resolved using methods for geosystem services valuation. Qualitative or semi-quantitative valuation methods can be used when monetary valuation is difficult or not possible. As a result, a well-informed strategic decision on sustainable and efficient use of resources in the subsurface is possible and the priorities thus set can be clearly communicated to all stakeholders through the plans. To increase the transparency of the decision-making process, it is important to document any inventory and valuation results and make them available to stakeholders.

It is worthwhile to emphasise that while extraction of geomaterials has been (and is) a major issue in natural resource economics (generally the provisioning services cover the extraction of materials, minerals, metals, and energy), other aspects of geosystem services have traditionally received less attention, such as abilities to regulate and support the environment. These services seldom have a market price but are, nevertheless, vital for humans and important to consider in strategic long-term planning. The comparison of the listed geosystem services in literature and the abiotic extension services of CICES V5.1 (Table 2) reveal that supporting geosystem services are omitted in the contemporary ecosystem services approaches, but to achieve a more holistic subsurface planning, also these are essential.

The added value of the ecosystem services concept is a systematic and holistic framework that results in transparent and comprehensive insights, not only into costs and benefits of decisions for different stakeholders and across different temporal and spatial scales (van der Meulen et al., 2016a), but also as a way of communicating complex systems. The similarities between the ecosystem services and geosystem services approaches may help in transferring conceptual knowledge and well-established valuation methods to support decision-making on the subsurface in spatial planning processes (van der Meulen et al., 2016a; van Ree et al., 2017). If we are to achieve sustainable development of cities and communities, the values of geosystem services must be made visible and acknowledged in spatial planning processes (Taromi Sandström et al., 2021).

5. Conclusions

The main conclusions drawn from this study are:

- There are two dominating definitions of geosystem services in literature. In the first definition (A), geosystem services are abiotic services that are the direct result of the planet's geodiversity, independent of the interactions with biotic nature – there is no differentiation between suprasurface and subsurface features. In contrast, in the second definition (B), geosystem services are considered to be only the goods and services that contribute to human well-being specifically resulting from the subsurface. Sochava's definition of geosystem (1974, 1978) as a unified dynamic whole of biotic and abiotic components of nature is not aligned with either of the definitions of geosystem services.

- Whereas definition A captures all nature's abiotic services to humankind, definition B needs to be complemented with abiotic services stemming from other spatial locations than the subsurface to fully reflect all different services the abiotic nature provides. From a subsurface planning perspective both definitions are useful, however, definition B is potentially easier to communicate.
- A unified definition of geosystem services is desirable and as a suggestion to explore further, the work on a unified definition could mimic the CICES approach to ecosystem services, where the definition of each service consists of both an "ecological clause", describing the biophysical output, and a "use clause", describing the contribution it makes to an eventual benefit.
- A coherent definition can facilitate the work on classification of geosystem services and such a definition classification framework has, in turn, the potential to serve as a tool for systematic inclusion of multiple geosystem services in planning processes, as well as support holistic subsurface planning.
- Thirty-one out of thirty-nine geosystem services listed in the reviewed literature are included in the abiotic extension of Common International Classification of Ecosystem Services CICES V5.1. The remaining eight geosystem services are not captured by CICES.
- Currently, there are examples of important geosystem services that are already considered in planning practice under the ecosystem services umbrella, as planners are aware of the importance to consider these in planning but lack other frameworks to put these abiotic services under.

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.

Data availability

Data will be made available on request.

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Appendix

Table A1
An overview of the 29 articles that were deemed relevant for this study and the corresponding search strings used in Scopus.

Authors	Title	Year	Search strings
Alahuhta J., Ala-Hulkko T., Tukiainen H., Purola L., Akujärvi A., Lampinen R., Hjort J.	The role of geodiversity in providing ecosystem services at broad scales	2018	Geodiversity, Abiotic service
Alahuhta J., Toivanen M., Hjort J.	Geodiversity–biodiversity relationship needs more empirical evidence	2020	Geodiversity
Bobylev, N.	Geosystem and ecosystem services-exploring opportunities for inclusion in urban underground space planning	2018	Geosystem
Boothroyd A., Henry M.M.	Old processes, new movements: The inclusion of geodiversity in biological and ecological discourse	2019	Geodiversity
Brilha J.	Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: a Review	2016	Geodiversity
Brilha J., Gray M., Pereira D.I., Pereira P.	Geodiversity: An integrative review as a contribution to the sustainable management of the whole of nature	2018	Geodiversity, Abiotic service
Chakraborty A., Gray M.	A call for mainstreaming geodiversity in nature conservation research and praxis	2020	Geodiversity
Crofts R.	Promoting geodiversity: Learning lessons from biodiversity	2014	Geodiversity
Fox N., Graham L.J., Eigenbrod F., Bullock J.M., Parks K.E.	Incorporating geodiversity in ecosystem service decisions	2020	Geosystem, Geodiversity, Abiotic service
Gordon J.E.	Engaging with Geodiversity: 'Stone Voices', Creativity and Ecosystem Cultural Services in Scotland	2012	Geodiversity
Gordon J.E., Barron H.F.	Valuing Geodiversity and Geoconservation: Developing a More Strategic Ecosystem Approach	2012	Geodiversity
Gordon J.E., Barron H.F.	The role of geodiversity in delivering ecosystem services and benefits in Scotland	2013	Geodiversity
Gray M.	Geodiversity: The backbone of geoheritage and geoconservation	2018	Geosystem
Gray M.	Valuing Geodiversity in an 'Ecosystem Services' Context	2012	Geosystem, Geodiversity, Abiotic service
Gray M.	Other nature: Geodiversity and geosystem services	2011	Geosystem, Geodiversity
Gray M.	The confused position of the geosciences within the "natural capital" and "ecosystem services" approaches	2018	Geodiversity
Gray M.	Geodiversity: Developing the paradigm	2008	Geodiversity
Gray M.	Geodiversity: The origin and evolution of a paradigm	2008	Geodiversity
Gray M., Gordon J.E., Brown E.J.	Geodiversity and the ecosystem approach: The contribution of geoscience in delivering integrated environmental management	2013	Geodiversity

(*continued on next page*)

Table A1 (*continued*)

Authors	Title	Year	Search strings
Hjort J., Gordon J.E., Gray M., Hunter M. L., Jr.	Why geodiversity matters in valuing nature's stage	2015	Geodiversity, Abiotic service
Ollier, C.	Problems of geotourism and geodiversity	2012	Geodiversity
Schrodt F., Bailey J. J., Daniel Kissling W., Rijsdijk K.F., Seijmonsbergen A. C., Van Ree D., Hjort J., Lawley R. S., Williams C.N., Anderson M.G., Beier P., Van Beukering P., Boyd D.S., Brilha J., Carcavilla L., Dahlin K.M., Gill J. C., Gordon J.E., Gray M., Grundy M., Hunter M.L., Lawler J.J., Monge-Ganuzas M., Royse K.R., Stewart I., Record S., Turner W., Zarnetske P.L., Field R.	To advance sustainable stewardship, we must document not only biodiversity but geodiversity	2019	Geodiversity
Smith A.C., Harrison P.A., Pérez Soba M., Archaux F., Blicharska M., Egoh B.N., Erős T., Fabrega Domenech N., György Á.I., Haines-Young R., Li S., Lommelen E., Meiresonne L., Miguel Ayala L., Mononen L., Simpson G., Stange E., Turkelboom F., Uiterwijk M., Veerkamp C.J., Wyllie de Echeverria V.	How natural capital delivers ecosystem services: A typology derived from a systematic review	2017	Abiotic service
van Ree C.C.D.F., van Beukering P.J.H.	Geosystem services: A concept in support of sustainable development of the subsurface	2016	Geosystem, Abiotic service
van Ree C.C.D.F., van Beukering P.J.H., Boekestijn J.	Geosystem services: A hidden link in ecosystem management	2017	Geosystem, Abiotic service
Volchko Y., Norrman J., Ericsson L.O., Nilsson K.L., Markstedt A., Öberg M., Mossmark F., Bobylev N., Tengborg P.	Subsurface planning: Towards a common understanding of the subsurface as a multifunctional resource	2020	Geosystem

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