Ecosystem Services 66 (2024) 101607

Contents lists available at ScienceDirect

Ecosystem Services

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

Review Paper

Valuation and management of desert ecosystems and their services

Haojie Chen [a], Robert Costanza [b,*]

[a] Oak Ridge Institute for Science and Education, 4955 Canyon Crest Drive, Riverside, CA 92507, United States
[b] Institute for Global Prosperity, University College London, London, WC1E 6BT, United Kingdom

ARTICLE INFO

Keywords:
Desert ecosystem services
Diversity of values
Payment for ecosystem services
Common asset trusts
Biodiversity
Geodiversity

ABSTRACT

Based on different definitions, deserts may constitute 13% to 33% of the global terrestrial surface. This is larger than the area of tropical forests and all types of wetlands combined. However, desert ecosystems are among the least studied in terms of their ecosystem services (ES), especially those that arise from species and processes unique to deserts. There are numerous research gaps that need to be filled including: (1) ignorance of unique desert ES, as well as deserts' special effects on ES; (2) limited application of sophisticated approaches for economic valuation of desert ES; and (3) lack of diverse approaches to values and valuation. Moreover, payment for ecosystem services (PES) schemes are often used to combat desertification rather than for conserving well-functioning deserts. Valuation of desert ES is crucial to implementation of PES through raising awareness of overlooked deserts, motivating investment, designing payment amounts, and estimating the social benefit-cost ratios of payments. In addition to market-based voluntary PES, common asset trusts (CATs) following Ostrom's eight core design principles may also contribute to sustainable management of desert ecosystems. Future research should explore unique desert ES, investigate the relationships between desert ES and geosystem services, improve accuracy of economic valuation of desert ES, and integrate diverse perspectives of values. The research results may potentially aid in both combatting desertification and conserving important deserts.

1. Introduction

The main types of deserts include warm and dry deserts, semi-arid deserts, coastal deserts, and cold deserts (Fig. 1). The variations in climate, geography, and ecosystems of deserts can result in different perceptions and interpretations of deserts, making deserts a relatively difficult biome to define precisely (Cioruța and Coman, 2020). However, deserts typically "consist of arid landscapes with a sparse plant cover, except in depressions where water accumulates. The sandy, stony or rocky substrate contributes more to the appearance of the landscape than does the vegetation" (IUCN, 2012).

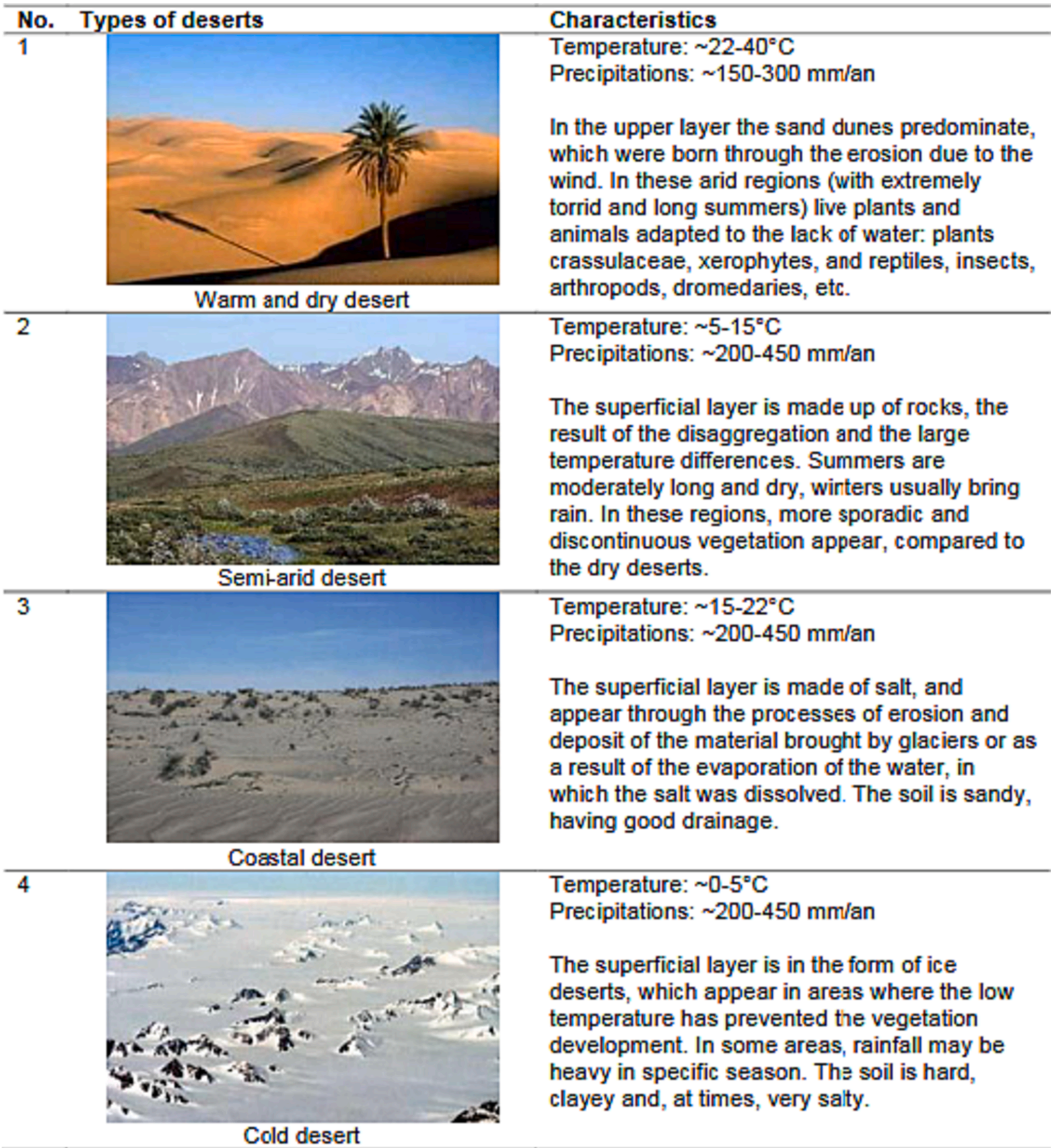
Depending on how land areas are classified into deserts, deserts may cover 13 % (Costanza et al., 2014), 20 % (National Geographic, 2023a), or 33 % (Alsharif et al., 2020) of the global terrestrial surface. The major deserts are distributed across the Sahara, the Arabian Peninsula, Western Asia, Southwestern Africa, Central and Southern Australia, Argentina, the Southwestern United States, and Northern Mexico (Keith et al., 2020). See Fig. 2 for their locations. Deserts not only contain important biodiversity (including some of the most endangered species), geodiversity, and ecosystem services (ES), but are also home to 6 % of the global population, including some of the poorest and most marginalised people (Durant et al., 2012; Lortie et al., 2020; United Nations, 2010). It is critical to understand their functions, global roles, and values, and to manage them sustainably.

ES are the benefits humans receive from ecosystems (Costanza et al., 1997b; Millennium Ecosystem Assessment, 2005). Of note is that this concept makes the wellbeing of humans and other species and ecosystems interconnected and reframes the relationships between humans and the rest of nature (Costanza et al., 2014). ES valuation, the activities of assessing ES values, has also been widely used to assist with ecosystem management, including raising awareness of nature conservation, assessing benefits and costs of different resource use approaches, integrating environmental value into socioeconomic decision-making, and measuring management effectiveness (Chen et al., 2023; Costanza et al., 2014; Hernández-Blanco et al., 2022; United Nations SEEA-EA, 2021).

A better understanding of the functions and values of desert ES can benefit management of land uses and resources in deserts and ultimately contribute to the sustainable wellbeing of humans and other species. However, deserts are often overlooked compared to other types of ecosystems, in terms of their biodiversity, ecological importance, and

* Corresponding author.
E-mail address: rcostanz@gmail.com (R. Costanza).

https://doi.org/10.1016/j.ecoser.2024.101607
Received 17 April 2023; Received in revised form 13 February 2024; Accepted 14 February 2024



No.	Types of deserts	Characteristics
1	Warm and dry desert	Temperature: ~22-40°C Precipitations: ~150-300 mm/an In the upper layer the sand dunes predominate, which were born through the erosion due to the wind. In these arid regions (with extremely torrid and long summers) live plants and animals adapted to the lack of water: plants crassulaceae, xerophytes, and reptiles, insects, arthropods, dromedaries, etc.
2	Semi-arid desert	Temperature: ~5-15°C Precipitations: ~200-450 mm/an The superficial layer is made up of rocks, the result of the disaggregation and the large temperature differences. Summers are moderately long and dry, winters usually bring rain. In these regions, more sporadic and discontinuous vegetation appear, compared to the dry deserts.
3	Coastal desert	Temperature: ~15-22°C Precipitations: ~200-450 mm/an The superficial layer is made of salt, and appear through the processes of erosion and deposit of the material brought by glaciers or as a result of the evaporation of the water, in which the salt was dissolved. The soil is sandy, having good drainage.
4	Cold desert	Temperature: ~0-5°C Precipitations: ~200-450 mm/an The superficial layer is in the form of ice deserts, which appear in areas where the low temperature has prevented the vegetation development. In some areas, rainfall may be heavy in specific season. The soil is hard, clayey and, at times, very salty.

Fig. 1. Desert categories (Cioruța and Coman, 2020).

contributions to socioeconomic development (UNEP, 2021a). To address this gap, we reviewed studies associated with desert ES and their valuation.

2. Methods

To find literature for our review, we used Scopus to search for terms in the title, abstract, and keywords without setting a time frame. Specifically, we searched for "“desert” AND “ecosystem service” AND “valuation”" (these terms are directly linked with the research topic) and found only 29 results, all of which were reviewed. To assess whether valuation is commonly integrated into desert ES studies, we expanded the search by searching for ““desert” AND “ecosystem service”” and found 530 results. We also searched for ES valuation studies related to other types of ecosystems using the terms in Table 1 to compare deserts with other types of ecosystems. However, ES studies specific to other types of ecosystems were not reviewed here. Then, we analyzed what issues existing desert ES valuation studies have addressed, identified what gaps remain in research, and explored how ES valuation can be applied to manage deserts.

3. Spatial distribution of studies associated with desert ecosystem services

Fig. 3 and Fig. 4 display the numbers of desert ES studies and desert ES valuation studies conducted by different countries or regions, respectively. Please note that in this context, “desert ES studies” or “desert ES valuation studies” are associated with, rather than necessarily specialized in, desert ES. Many of these studies only involve general discussions of desert ES without a specific study area or a geographical location of deserts. Therefore, Fig. 3 and Fig. 4 do not necessarily reflect which countries’ deserts have been studied the most frequently, but rather which countries exhibit research interest in desert ES. Moreover, the numbers in Fig. 3 and Fig. 4 count studies co-authored by multiple countries for multiple times. For example, a study involving coauthors from China and the United States contributes to the numbers for both countries.

3.1. A highlight of China

It is noteworthy that that China has contributed the largest number

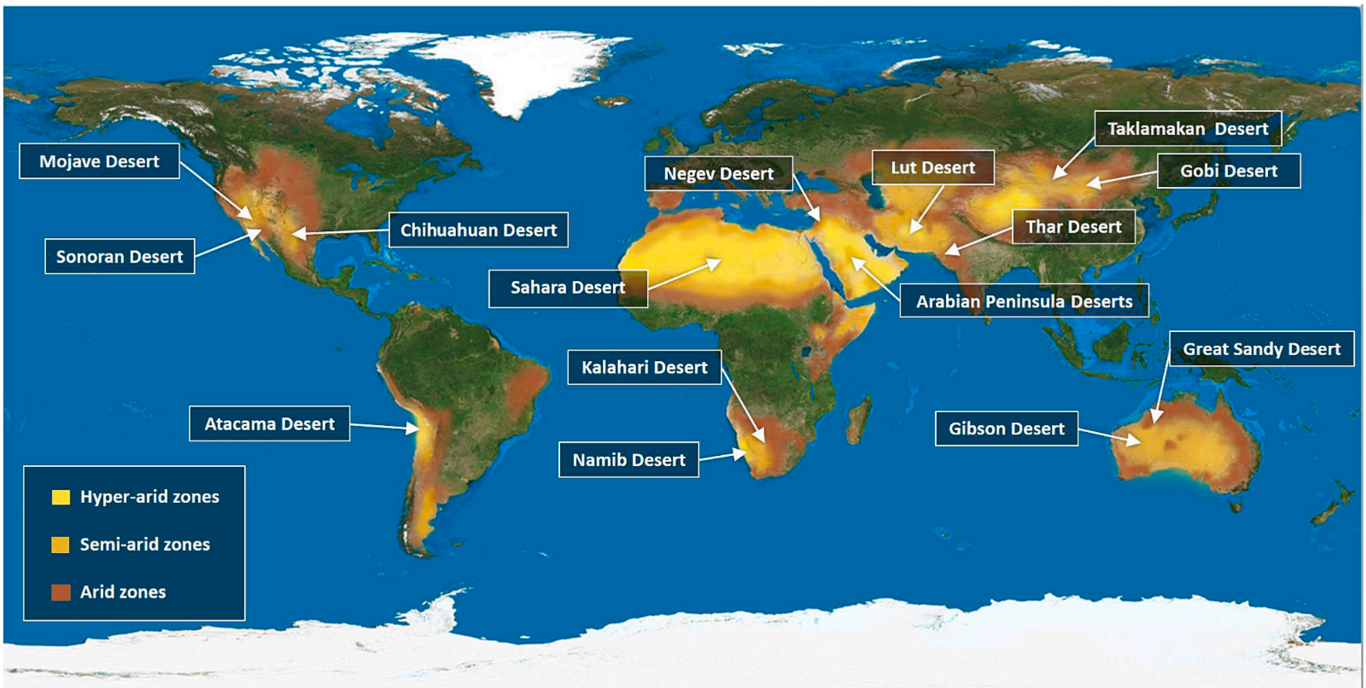


Fig. 2. Locations of major global deserts. The map is adapted by Alsharif et al. (2020) from an earlier version of the World Atlas of Desertification (Cherlet et al., 2018).

of studies in the field of desert ES especially desert ES valuation. Specifically, China has contributed to nearly 50% of the desert ES studies we have identified and over 70% of the desert ES valuation studies. This indicates that China stands as a frontrunner among nations, paying more attention to desert ES in its decision-making and incorporating ES valuation into its desert management strategies. China has also developed several guidelines on accounting for ES values, and of note is the *Assessment Standards of Desert Ecosystem Services* (Chinese Academy of Forestry, 2012), which is specific to desert ES. This guideline may be a potential reference for other countries to value desert ES, hence we highlight it below.

The guideline suggests assessing several desert ES in both biophysical (e.g., volume of water/ha/yr) and monetary units. These ES included soil conservation, wind breaks and sand fixation, water regulation, carbon fixation, biodiversity conservation, and tourism. Associated monetary valuation techniques are also suggested, including the market price method, the alternative cost method, and the avoided social cost method. This guidance can be useful in many situations but also contains the following limitations:

(1) Soil conservation may overlap with sand fixation (Chen, 2020a).
(2) Value of biodiversity conservation is to some extent already included in the values of provisioning, regulating and cultural services (Costanza et al., 2017). This makes valuing biodiversity conservation more complex.
(3) Water regulation contains a set of more specific ES, including at least water retention, flood control, and water purification, hence it may not always be proper to assess water regulation as a single service.
(4) Deserts may contain areas of grasslands, woodlands, wetlands, and farmlands (UNEP, 2015), hence more ES may be incorporated.

The reasons behind China's relatively large number of desert ES valuation studies may include the following. (1) China has committed to achieve an ecological civilization initiative, which is a vision of society with integrated development of both humans and the rest of nature, long-term prosperity, and environmentally conscious citizens. This initiative recognizes that nature provides essential benefits to humans and emphasizes that all types of ecosystems are interconnected (Chinese Ministry of Ecology and Environment, 2020; Hansen et al., 2018). (2) An important approach to realize this initiative is the comprehensive assessment of ES values across the entire country. In China, these values are often referred to as the Gross Ecosystem Product (GEP) and have been applied in some pilot regions, such as Shenzhen City and Lishui City, serving as a complementary indicator to Gross Domestic Product (GDP) for measuring development, government performance, and land-use quality (Chen et al., 2022; Ouyang et al., 2020; Zou et al., 2020). (3) Covering roughly 1.65 million km^2, deserts are approximately 17% of China's land area and represent a crucial component of China's ecosystems (Cheng et al., 2020). (4) The Chinese government has recognized desert management as a pivotal approach to improve living standards, environmental quality, and economic performance, especially since ratifying the United Nations Convention on Combating Desertification in 1997 (Chinese Central Government, 2023; Kong et al., 2021; UNEP, 2015).

Why desert ES valuation studies in the rest of world appear to be quite limited requires further investigation, and several potential factors may contribute to this phenomenon. (1) Numerous countries lack significant desert areas (Fig. 2), leading to a diminished policy need or research interest in desert ES. (2) Deserts may be perceived as lifeless and marginalized regions, because of their sparse vegetation, water deficit (hot deserts typically lose more moisture through evaporation than they receive from precipitation), limited nutrients for many species to live, and unpleasant temperatures for humans (e.g., substantial temperature change from the day to the night, high temperature that can reach 50 °C in hot deserts, and temperature lower than 0 °C in cold deserts) (National Geographic, 2023b). This further diminishes their attractiveness for study. (3) In many regions, the shortage of financial and technological resources, as well as the absence of robust and reliable valuation methods, hinders research efforts (Pascual et al., 2023). This limitation can extend to desert ES research. (5) The delay in delivering valuation results in relation to decision timeframes, as well as failure of valuation results to meet the needs of policymakers, administrators, and

Table 1
Number of results based on the search on 24 October 2023 using SCOPUS.

Ecosystem types	Search terms	Number of results	Number of results after adding "AND "valuation"" to the previous search terms
Desert	"Desert" AND "ecosystem service"	524	29
	"Gobi" AND "ecosystem service"	15	0
	("Desert" OR "gobi") AND "ecosystem service"	531	29
Farmland	"Farmland" AND "ecosystem service"	1,330	105
	"Paddy field" AND "ecosystem service"	176	22
	"Cropland" AND "ecosystem service"	1,228	106
	"Orchard" AND "ecosystem service"	475	25
	"Cultivated land" AND "ecosystem service"	1,224	101
	("Farmland" OR "paddy field" OR "cropland" OR "orchard" OR "cultivated land") AND "ecosystem service"	3,537	312
Grassland	"Grassland" AND "ecosystem service"	3,538	238
	"Rangeland" AND "ecosystem service"	616	35
	"Pasture" AND "ecosystem service"	1,115	45
	"Grazing land" AND "ecosystem service"	126	16
	"Savanna" AND "ecosystem service"	444	10
	"Meadow" AND "ecosystem service"	798	38
	("Grassland" OR "rangeland" OR "pasture" OR "grazing land" OR "savanna" OR "meadow") AND "ecosystem service"	5,657	356
Marine	"Marine" AND "ecosystem service"	3,212	319
	"Coastal" AND "ecosystem service"	4,733	499
	"Estuary" AND "ecosystem service"	833	62
	"Coral reef" AND "ecosystem service"	670	62
	("Marine" OR "coastal" OR "estuary" OR "coral reef") AND "ecosystem service"	6,913	666
Urban	"Urban" AND "ecosystem service"	8,537	633
	"City" AND "ecosystem service"	5,336	423
	("Urban" OR "city") AND "ecosystem service"	9,640	801
Freshwater	"Freshwater" AND "ecosystem service"	1,961	116
	"Lake" AND "ecosystem service"	2,083	201
	"River" AND "ecosystem service"	5,432	536
	("Freshwater" OR "lake" OR "river") AND "ecosystem service"	7,880	752
Wetland	"Wetland" AND "ecosystem service"	4,246	464
	"Floodplain" AND "ecosystem service"	614	37
	("Wetland" OR "floodplain") AND "ecosystem service"	4,608	481
Forest	"Forest" AND "ecosystem service"	13,392	1,075
	"Woodland" AND "ecosystem service"	1,028	71
	"Shrub" AND "ecosystem service"	1,018	50
	"Bush" AND "ecosystem service"	103	6
	("Forest" OR "woodland" OR "shrub" OR "bush") AND "ecosystem service"	14,469	1,136

Note: We classified ecosystem types according to Costanza et al. (2014) and Keith et al. (2020).

stakeholders, can serve as additional barriers to further research (IPBES, 2022).

4. Gaps in valuation of desert ecosystem services

Overall, there are a limited number of desert ES valuation studies with several gaps. These gaps include a restricted acknowledgment of the unique and distinct contributions of deserts to ES, a disregard for option and non-use values associated with ES, a lack of diverse valuation perspectives and units, and a lack of sophisticated valuation methodologies.

4.1. Limited number of studies valuing desert ES

We observed the emergence of desert ES studies in 1998, with a gradual increase over time, particularly since 2012. Desert ES valuation studies started in 2008 and have been growing with a slow rate (Fig. 5). However, deserts are still among the least intensively studied ecosystems in terms of their biodiversity, ES, and especially ES values (Cheng et al., 2013; Durant et al., 2012; Murdoch et al., 2017; Taylor et al., 2017). ES studies of other ecosystem types are at least 6 times that of deserts (Table 1). Among the 29 studies related to desert ES valuation we found, 20 of them assessed desert ES values and are summarized in Table 2.

4.2. Limited incorporation of deserts' unique contributions to ES

As shown in Table 2, the existing desert ES valuation studies often only consider the most frequently estimated ES that are commonly integrated into all ES valuation studies regardless of ecosystem types. These ES include provisioning of food, raw materials, and medicine resources, climate regulation, carbon sequestration, water regulation and retention, soil retention and formation, waste treatment, air quality regulation, recreation, tourism, and aesthetics.

However, while the concept of ES covers ecosystem's contributions to human health (World Health Organization, 2015), we did not find any studies that assessed the impacts of desert health on zoonotic diseases or human health. Evidence has shown that desert health affects human health by affecting water, food and natural medicine provisioning, quality of air, natural disaster occurrence (especially sandstorms), and risk of zoonotic disease (Hernández-Blanco et al., 2022; UNEP, 2006, 2015). In particular, the Covid-19 pandemic highlighted the connection between zoonotic diseases and ecosystem health. Desert-related zoonotic diseases include epidemics and loss of nutrition sources caused by outbreaks of desert locusts, the desert sub-type of zoonotic visceral leishmaniasis, and zoonotic pathogens in camels' tissues and blood (Bahari et al., 2021; Kassegn and Endris, 2021; Wang et al., 2010; Xu et al., 2021).

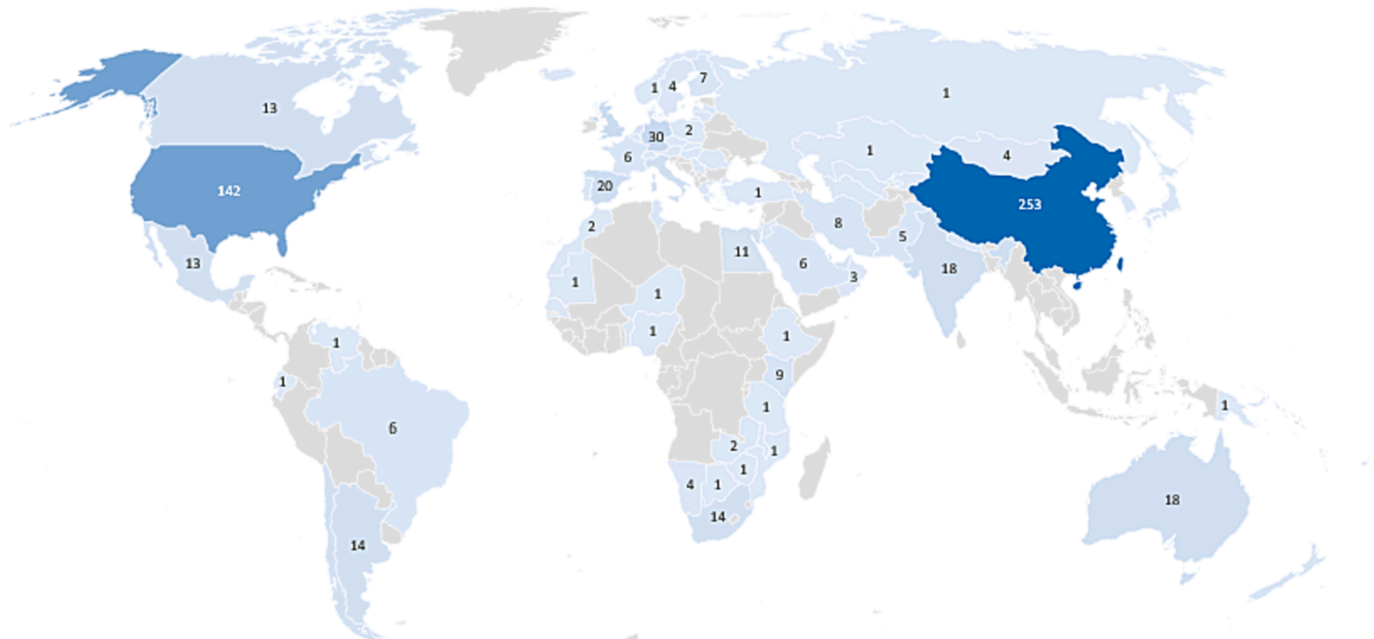


Fig. 3. Number of desert ES studies conducted by researchers from different countries/regions (due to limited space, this map does not fully show all the numbers).

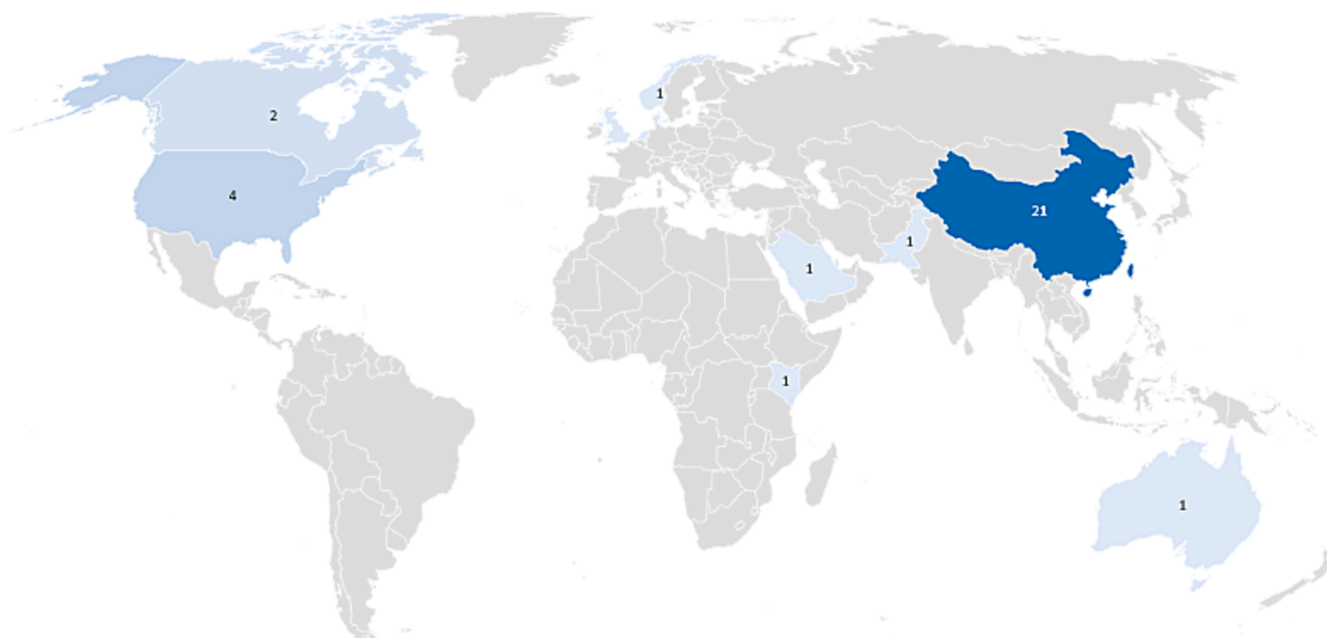


Fig. 4. Number of desert valuation ES studies conducted by researchers from different countries/regions.

We did not find any assessments of the values of diverse genetic resources in deserts, such as the scientific values of drought and salt-tolerant species. While deserts in the popular mind are often thought to be lifeless, deserts in fact play an important role in biodiversity conservation. For example, according to UNEP (2021a), the Sahara is the home for 500 plant species, 70 known mammalian species, 100 reptilian species, 90 avian species, and several arthropods (e.g., spiders and scorpion). Many of them are unique to desert ecosystems with special scientific values and at risk of extinction.

Moreover, we did not find any value assessments of the following special contributions of deserts to ES. These contributions may also be classified as geosystem services and include (1) water condensed in soil and sand, which is not only about water provisioning but also crucial to the stability of sand dunes and maintenance of food chains in deserts. (2) Global biogeochemical cycles involve desert sand (e.g., iron-rich nanoparticles in aeolian mineral dust can fertilize marine water and promote phytoplankton blooms, which in turn influences carbon sequestration, oxygen production, and marine productivity). (3) Seed banks in deserts are important since sand contains and disperses seeds, influencing persistence and abundance in the gap phase or metapopulation dynamics, rates of invasion and colonization, and biodiversity. Finally, (4) deserts are important in neutralization of rain acidity that affects species health (Aragón-Gastélum et al., 2018; Baddock et al., 2013; Cheng et al., 2013; Cheng et al., 2020; Haight et al., 2019; Taylor et al., 2017; Terada et al., 2002; Venable et al., 2008; Yao, 2020). Ignorance of these contributions may lead to an underestimate of deserts' importance and

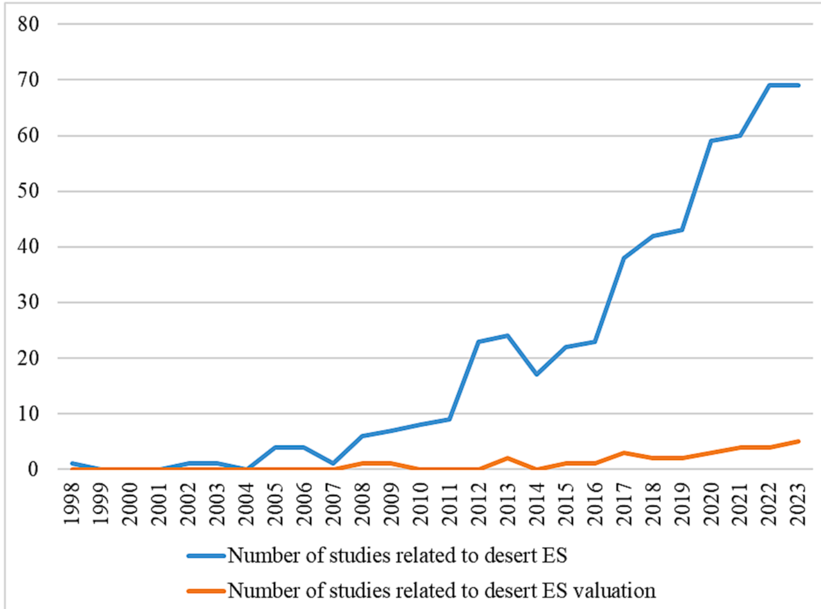


Fig. 5. Number of relevant publications since 1998.

irreplaceability and a biased perception of deserts' roles in global ecosystems.

These issues are, of course, not unique to deserts. As we learn more about ecosystems and their complex interconnections with human wellbeing, we are constantly discovering unique ecosystem functions and features that increase their values. Therefore, we may consider many valuations of ES to be conservative underestimates (Costanza et al., 1997a; Costanza et al., 2014) and employ precautionary policies to acknowledge our continuing limited knowledge. Nevertheless, deserts may suffer most from these limitations given their relative lack of attention. Decision-making based on these limitations runs the risk of sacrificing deserts' contributions to ES and wellbeing of humans and other species.

4.3. Limited application of sophisticated economic valuation methods

All valuation methods make simplifying assumptions and there is a trade-off between the degree of precision of the valuation and the cost involved in making the assessment (Kubiszewski et al., 2022). Economic valuation methods in the exiting desert ES literature (Cheng et al., 2013; Jordaan et al., 2021; Mamat et al., 2021; Peng et al., 2010; Sawut et al., 2013; Taylor et al., 2017) tend to assume a constant unit value of ES that is independent from ES quantity. This assumption is popular because it makes valuation more practical and less costly than more sophisticated methods (Kubiszewski et al., 2022; Ouyang et al., 2020; Turner and Daily, 2008), or methods that account for the fairness and sustainability of the ES (Costanza, 2020). However, this assumption may ignore:

(1) ES synergies (the simultaneous increment or diminishment of biophysical supply of multiple ES, especially regulating ES) and trade-offs (increasing the biophysical supply of one ES is at the expense of reducing another, especially among regulating and provisioning ES) (Bennett et al., 2009; Chen, 2020b; Fu et al., 2018; Stosch et al., 2019),
(2) non-linearity between the quantity and value of ES, as the marginal value of an ES may be diminishing when the quantity of the ES is abundant, or increasing when the ES quantity is approaching a threshold (Farley, 2012; Liu et al., 2007),
(3) non-constant physical, chemical and ecological status of deserts under climate change, such as population growth rate of desert plants affected by variable precipitation, seed germination affected by soil warming, decline of some desert animals' populations, and spatial shifting of deserts (Aragón-Gastélum et al., 2018; Dagvadorj et al., 2009; Iknayan and Beissinger, 2018; Salguero-Gomez et al., 2012; Taylor et al., 2017),
(4) consideration of species identities and traits.

In particular, the constant-unit-value assumption is often integrated into benefit transfer methods. Such benefit transfer methods multiply a constant unit value/ha/yr (Table 3) of a type of ecosystem estimated previously by the total area of the ecosystem to aggregate the total value of a subset of ES in a certain year (Costanza et al., 1997b; Costanza et al., 2014). However, as benefit transfer methods are based on existing value estimates of ES and hence may not be applicable deserts' unique ES or special contributions to ES (e.g., those mentioned in Section 4.2) that have not been studied before. Cultural ES have especially lower transferability than provisioning and regulating ES (Farber et al., 2006), as the cultural characteristics of deserts may not be replaced by other types of ecosystems (Yao, 2020).

4.4. Lack of diverse views of desert values

Different perspectives exist regarding how we value the rest of nature. These perspectives may focus on human wellbeing, which is the essence of the definition of ES, or they may emphasize that all living organisms have a right to exist – representing an intrinsic value. These perspectives are not mutually exclusive and we need plurality (Pascual et al., 2023). From an ES perspective, the rest of nature is essential to support sustainable human wellbeing. Humans are interdependent with the rest of nature. From a rights perspective, nature possesses intrinsic value and must be protected for its own sake. Relational values express the significance of relationships between people and the rest of nature or among people through the rest of nature, and hence can embody both ES- and rights-based perspectives (IPBES, 2022). There is also a distinction between use values focusing on utilizing something and non-use values attributed to the mere existence of something, bequest (for future generations), or for altruistic purposes (Marre et al., 2015; United Nations SEEA-EA, 2021). Option values refer to the values of preserving something for future benefits (de Groot et al., 2010), and hence can be viewed as instrumental when emphasizing the future use of something

Table 2
Summary of desert ES valuation studies.

Studies	Study area	Valuation units	ES valuation results (the ES assessed are underlined in this column)
(Zhao et al., 2023)	Tibetan Plateau, China	Biophysical unit (tonne)	During 2000–2020, the desert shrub and non-vegetation area expanded by 63.21% and 13.35%, respectively, while the deciduous scrub, mixed forest, and low-coverage grassland decreased accordingly. The carbon storage of the Tibetan Plateau showed a decreasing trend by 370,000 tonnes.
(Yan and Li, 2023)	Central Asia, including Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan	Biophysical unit (tonne)	104.46 mm/km2 of water yield and 60.09 tonnes of soil retention in desert steppe region; 49.48 mm/km2 of water yield and 34.75 tonnes of soil retention in desert region.
(Wei et al., 2022)	Jiziwan that overlaps with four deserts: Tengger, Ulan Buh, Kubuqi, and Mu Us, China	Biophysical unit (land area)	From 2000 to 2020, the rates of change in areas of poor, bad, moderate, good, and excellent habitat quality were −10.53%, 6.18%, 1.78%, −55.66%, and 54.22%, respectively, due to land use change.
(Zhang and Chen, 2022)	The Tarim River Basin that consist of nine water systems and the Taklimakan Desert, China	Biophysical unit (habitat quality index)	Since 2000, the Tarim River Basin has experienced a declining trend in habitat quality index from 0.449 to 0.444 due to agriculture expansion that has exacerbated desertification
(Addas, 2022)	Urban parks in Jeddah, a desert megacity of Saudi Arabia	Time spent	Urban parks were mostly used for spending time with relatives and friends (21.26%), followed by mental rejuvenation and relaxation (13%), physical activity (11.82%), accompanying children (9.58%), experiencing nature and its aesthetic beauty (7.36%), and picnics (6.06%)
(Zhai et al., 2022)	A polluted desert site in Gansu, China	Monetary unit (CNY)	Pollution caused value loss of climate regulation and soil conservation by 405,049 CNY in total.
(Zhu et al., 2021)	Arid region in northwestern China	Biophysical unit (tonne)	The desert areas had the lowest capacity to sequester and store carbon compared to other types of lands.
(Aziz, 2021)	Nationwide terrestrial ecosystems of Pakistan	Monetary unit (USD)	The unit value of desert ES was $525/ha/year in total (this value considers water provisioning, water regulation, and climate regulation) and lower than that of other types of ecosystems. Expansion of desert areas can lead to a decline in the value of total ES.
(Mamat et al., 2021)	A mountain-oasis-desert ecosystem of the Kaidu–Kongque River Basin, China	Monetary unit (USD)	The unit values/ha/yr of Gobi ES included water supply at $5, waste treatment at $17, climate regulation at $9, biodiversity protection at $26, recreation at $16, soil formation at $11, gas regulation at $4, food production at $1, and raw material at $3. The value of the total Gobi ES declined from $328 million in 1978 to $323 million in 2018 due to loss of Gibi area.
(Zhou et al., 2020)	The Shiyang River Basin that includes several deserts in Northwest China	Biophysical unit (tonne)	Restoration of desert vegetation, grasslands, and woodlands together increased carbon storage by 14 million tonnes from 2000 to 2016
(Cheng et al., 2020)	Nationwide deserts in China	Monetary unit (CNY)	The value of China's desert ES in 2014 was 4227.9 billion CNY (in 2014 prices), of which, wind break and sand fixation, hydrological regulation, soil conservation, and carbon sequestration consisted of 40.1 %, 24.2 %, 18.1 % and 17.0 %, respectively, and biodiversity conservation and landscape recreation together accounted for less than 1 %.
(Schild et al., 2018)	Review of multiple studies worldwide	Monetary units (USD)	The unit values/ha/yr of desert ES included raw material provisioning at $15, water regulation at $232, biological regulation at $1, and cultural benefits (recreation, tourism, hunting, aesthetic and inspirational service) at $24.
(Ma et al., 2017)	Nationwide deserts in China	Monetary units (CNY)	The ES values of 2.1 million km^2 of deserts in China included carbon sequestration and oxygen production at 117,830 million CNY, soil retention at 104,230 million CNY, wind break and sand fixation at 135,070 million CNY, and air purification at 4380 million CNY in 2015.

(continued on next page)

Table 2 (*continued*)

Studies	Study area	Valuation units	ES valuation results (the ES assessed are underlined in this column)
(Jiang et al., 2017)	The Three-river Headwater Region, which contains desert areas, China	Biophysical unit (tonne and habitat quality index)	Overall, water retention, soil retention, wind break and sand fixation, and habitat quality of the whole study region improved from 2000 to 2010, but the results specific to deserts were not provided.
(Cuni-Sanchez et al., 2016)	Mt Nyiro, Mt Kulal, and Mt Marsabit located in desert area of northern Kenya	Importance ranking	Water provisioning was always ranked at the most valuable by all groups. Provisions of firewood, medicine resources, and fodder were also highly ranked; Aesthetic values and air purification were the least recognised. The ES ranked in the middle included provisioning of food, shade, shelter during conflicts, soil formation, and microclimate regulation.
(Li et al., 2015a)	Qinghai-Tibetan Plateau, China	Biophysical unit (tonne)	Alpine meadows provided a larger amount of water provision, carbon storage, and better habitat quality than alpine deserts.
(Sagie et al., 2013)	The Arava valley on the southern border between Israel and Jordan	Perception of ES	The residents felt that their environment is abundant in ESs, especially cultural ES (spiritual/tradition, mental wellbeing, education/research, recreation/sports, tourism, aesthetics, and sense of place). Provisioning ES (food, energy, raw material, water, and natural pharmaceuticals/ cosmetics) were also perceived, whereas supporting and regulating ES were rarely recognized.
(Sawut et al., 2013)	The Ugan-Kuqa River Delta Oasis, China	Monetary unit (CNY)	The unit values/ha/yr of Gobi ES included water supply at 27 CNY, waste treatment at 9 CNY, biodiversity protection at 301 CNY, recreation at 9 CNY, soil formation at 18 CNY, and food production at 9 CNY. The value of the total Gobi ES declined from 68 million CNY in 2002 to 67 million CNY in 2008 due to loss of Gibi area.
(Niu et al., 2009)	Gansu Province, China	Monetary unit (CNY)	The unit values/ha/yr of desert ES included water retention at 27 CNY, environmental purification at 9 CNY, biodiversity protection at 301 CNY, culture and entertainment at 9 CNY, soil formation and conservation at 18 CNY, and organic products at 9 CNY. Areas with larger deserts tended to have lower ES values.
(Dodds et al., 2008)	North American deserts	Monetary unit (USD)	The unit values/ha/yr of desert ES were estimated to consist of disturbance regulation at $2, water supply at $85, nutrient cycling at $60, recreation at $16, and soil erosion control at $237.

or intrinsic or rights-based when highlighting its significance as a legacy to be passed on for its own sake.

However, in the non-economic studies shown in Table 2, most of the focus is on the instrumental values of deserts. Only Sagie et al. (2013) and Cuni-Sanchez et al. (2016) assessed the relational values of deserts, such as traditional and spiritual connections with deserts. The economic studies on desert valuation have primarily concentrated on the use values, although a few studies, such as Richardson (2005) and Kroeger and Manalo (2007), explored the non-use values or option values of deserts. The focus on use values is common across ES studies, regardless of the type of ecosystem (Pascual et al., 2023). In economic valuation, non-use and option values are often assessed using stated-preference surveys that infer people's willingness to pay by asking people to express preferences in hypothetical scenarios (Johnston et al., 2017). Conducting such surveys may be time-consuming and expensive, and the survey results are not always realistic (Bishop et al., 1997; Chan et al., 2011; Chen et al., 2022). When assessing desert ES, option and non-use values may be further ignored. This may be because of a biased image that deserts are less important than other ecosystems and a misconception that combating desertification means converting all deserts into green lands. In addition, non-use and option values are not always positively correlated with use values. For example, tourism requires access (e.g., roads) to natural areas and may change landscapes and reduce vegetation biomass (Chen, 2020a; de Groot et al., 2010). Therefore, merely focusing on use value may compromise non-use and options values in the long term.

The lack of diverse views of values is also reflected by the limited valuation units in existing desert ES valuation literature. Although value has many meanings and can be expressed in various units, monetary units are the most commonly used in the field of ES valuation (Costanza, 2020). It is also true for desert ES valuation. Nine studies in Table 2 used monetary units, followed by seven studies using biophysical units. Only three studies utilized other types of valuation ways. Monetary units have several strengths, including convenience for communication with a wide audience, allowing for comparison of environmental and financial benefits and costs in the same unit, assistance to trading off natural and other capital, and raising awareness of ES (Costanza et al., 1997a; Costanza et al., 2014; de Groot et al., 2012). However, monetary units alone are not sufficient to shape a comprehensive view of desert ES especially in a complex and multi-dimensional human-nature system. For instance, in many regions in the world, such as Uluru-Kata Tjuta National Park in Australia, the Negev Desert in Israel, and the Thar Desert in India, indigenous people, seekers, thinkers, explorers, poets,

Table 3
Unit values (US$$_{2020}$/ha/yr) of desert ES compiled from the Ecosystem Services Valuation Database (https://www.esvd.info/).

ES	Minimum values	Maximum values	Mean values	Median values	Standard deviations	Number of value estimates
Raw material provisioning	6	139	37	26	33	23
Surface water for drinking	23	3,542	563	265	890	21
Maintenance of soil fertility	1	1241	621	621	877	2
Maintenance of genetic diversity	36	36	363	36	NA	1
Existence and bequest	0.03	85	15	0.305	34	6

Note: There are other potential services (e.g., air purification), but they are not included in the table above due to the lack of existing value estimates.

artists, prophets, and tourists may not only obtain benefits from deserts but also build sacred relationships with these areas (Gehlot et al., 2014; Jasper, 2008; Sinamai, 2017). These spiritual and cultural values might not be best expressed in monetary units, even if some estimates in monetary units are possible.

Acknowledging that desert ES have spiritual and religious values does not mean that they lack use and non-use values that can be expressed in monetary units, and *vice versa*. Given the complexity of social, economic and ecological contexts and the diverse ways people perceive, experience, and interact with the rest of nature, including deserts, there is no one-size-fits-all value unit or universally right way to value ES. However, there is a wrong way – not to value them at all. Different value units and approaches are not mutually exclusive, but rather complementary to make a wider diversity of values visible and enhance the quality of the valuation results to support decisions about deserts. The recently adopted Kunming-Montreal Global Biodiversity Framework emphasizes the necessity of integrating diverse values into policies, regulations, planning, and development at all levels and sectors for a shared, healthy, and sustainable future for life on Earth (CBD, 2022b). This integration is inclusive of desert management, as discussed below.

5. Desert management and application of ecosystem service valuation

The research gaps in desert ES valuation leave a biased view of deserts' roles in interaction with global ecosystems and an underestimate of deserts' contributions to the wellbeing of people and the planet. However, these gaps should not preclude movement to better study and management of desert ecosystems to protect and enhance their ES. Many environmental issues are the by-products of socioeconomic development (Chen, 2020b), which may underestimate or ignore the contributions of life-supporting ecosystems, especially those that are indirect and invisible to people. Therefore, ES valuation that visualizes ecosystems' hidden benefits, links ecosystems with human wellbeing, and connects ecosystem management with socioeconomic development is essential to desert management strategies.

We classify desert management strategies into two main categories: combating desertification and conserving deserts. This classification is based on whether the strategies address issues related to the contraction or expansion of desert areas and whether they aim to maintain or reduce the extent of deserts. Section 5 describes some major global initiatives and strategies associated with combatting desertification and desert conservation. It also discusses how ES valuation can be applied to the strategies.

5.1. Combatting desertification and conserving deserts

Desertification is increasing in many parts of the world, producing negative impacts on the livelihoods of 1.3 billion people globally (UNCCD, 2017a). These include poverty, health risks, food insecurity, water scarcity, forced migration, declined resilience to climate change, and conflict over diminishing resources (UNCCD, 2017c). Since 1994, 197 parties have signed the United Nations Convention on Combatting Desertification, the sole legally binding international agreement specifically addressing desertification (UNCCD, 2021). As part of the Sustainable Development Agenda, the world is also committed to "combat desertification, restore degraded land and soil" by 2030. The more recent *UNCCD 2018–2030 Strategic Framework* further demonstrates a global commitment to building "a future that avoids, minimizes, and reverses desertification/land degradation and mitigates the effects of drought" (UNCCD, 2017c).

A famous regional initiative is the "Great Green Wall" in sub-Saharan Africa. It aims to restore 100 million hectares of currently degraded land, sequester 250 million tons of carbon, and create 10 million green jobs by 2030 in an 8,000 km long strip (the world largest living structure) along the southern border of the Sahara Desert (UNCCD, 2020). While it is uncertain whether the GGW initiative will fully achieve its objectives, it has led to increased interest and research on large-scale land restoration in desert ecosystems.

The Central Asian Countries Initiative for Land Management, a collaborative effort involving central Asian countries and development partners (e.g., Asian Development Bank, Unted Nations), is also a noteworthy regional initiative dedicated to improving soil productivity and ES on 2.6 million hectares of drought-prone and salt-affected agricultural landscapes (ADB, 2005; UNCCD, 2017b). While it has not fully achieved its mission, it has made considerable advancements, such as greater accessibility to new agricultural technologies, reduced manual labour in farming, strengthened farming knowledge, and improved rural livelihoods (e.g., income from cultivation of new plants) (CACILM, 2016).

The highly drought-susceptible Latin American and the Caribbean region has developed regional drought-combatting collaboration, such as (1) the approval of the Declaration of Santa Cruz at the 2017 Regional Conference on Drought Management, urging Latin American countries to adopt proactive drought policies; and (2) the establishment of a regional flood and drought monitoring and warning system (Magalhaes, 2017). Moreover, countries in this region, including Argentina, Brazil, Chile, and Mexico, have developed national civil defence systems responsible for providing relief and requesting assistance or humanitarian aid (e.g., through declaring a state of emergency or public calamity) in case of a drought (Magalhaes, 2017).

A noteworthy country case is the Desert Green Economy Pilot Initiative in the Kubuqi Desert, China. This initiative has led to (1) ecological benefits: an area of more than 5,000 km^2 has been afforested, reducing dust storms, salinization of soil, and biodiversity loss; (2) economic growth of ecotourism, green agriculture, new building materials from sand, renewable energy (e.g., solar power), and pharmaceutical industry that processes desert medical herbs (e.g., licorice); (3) social benefits from new homes and schools; and (4) scientific progress in irrigation, plant species selection for desert greening, and breeding technology (UNEP, 2015). These achievements were attributed to technological and financial support, conformity to local geographic conditions (e.g., replanting drought-enduring vegetation), and engagement of governments, enterprises, research institutes, and communities (UNEP, 2015).

The rights, knowledge, and participation of indigenous people also play a crucial role in combating desertification. The Desert Aboriginal Land Management initiative empowers and engages aboriginal Australians in desert management and desert-based enterprises. This initiative

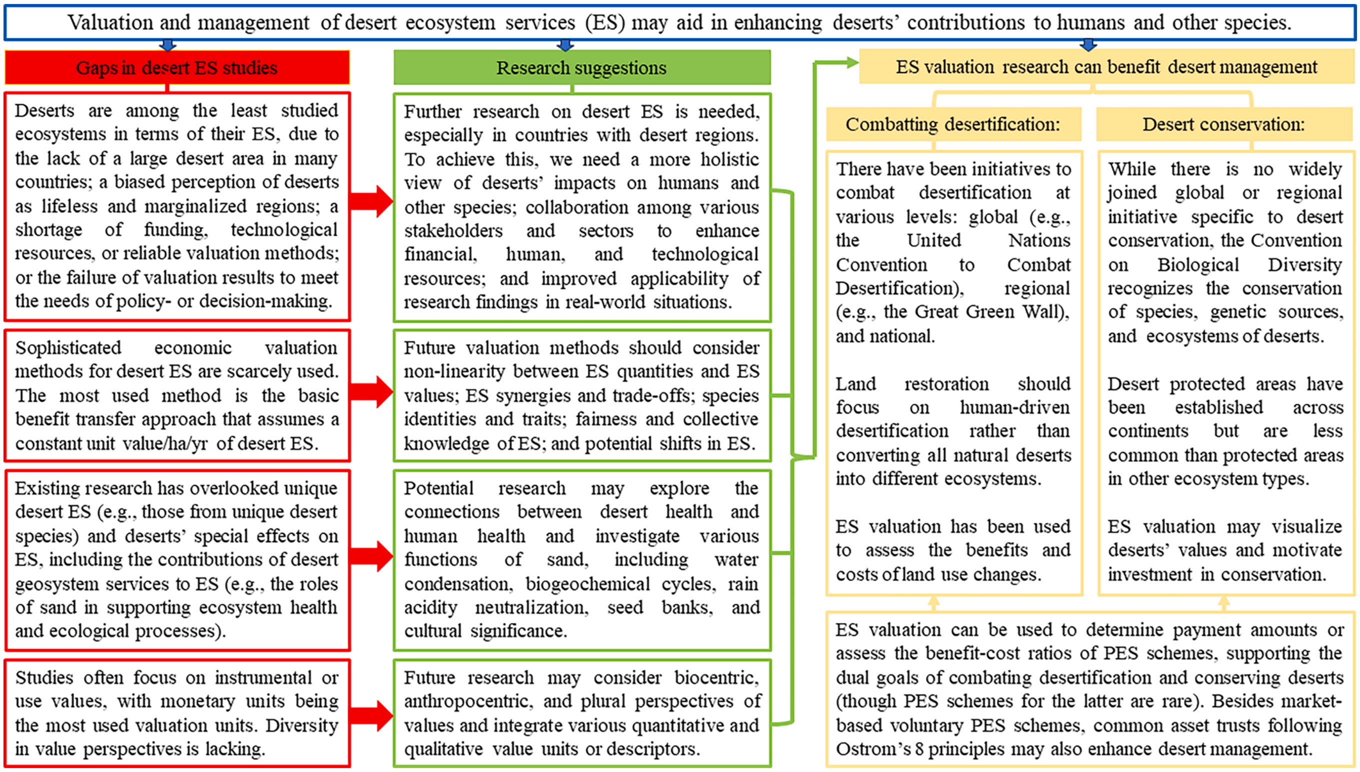


Fig. 6. Summary of this study.

has promoted desert ES conservation and economic development. It has also improved the wellbeing of aboriginal people, including their material livelihoods, mental health (e.g., maintenance of their sense of control over the lands), social equity between aboriginal and immigrant Australians, and protection of traditional knowledge and customs (Davies et al., 2011).

While combatting desertification has raised global awareness, it should not ignore the significant roles that natural deserts play in global ecosystems. We need to highlight the distinction between "natural deserts" and "human-driven desertification". Attempting to green entire natural deserts may not be ecologically, economically, or culturally desirable or sustainable for several reasons: (1) land greening that contributes to biodiversity is typically applied to degraded lands, rather than replacing natural ecosystems that serve as habitats for indigenous fauna and flora (Bremer and Farley, 2010); (2) natural deserts are inherently characterised by severe water limitation and low productivity (Martínez-Valderrama et al., 2020), making land greening and maintaining human-planted vegetation in these areas costly and challenging; (3) there are concerns about exacerbating water scarcity resulting from extensive greening projects in arid regions (Zastrow, 2019); (4) given the limited global funding available for combating desertification (UNCCD, 2023), funding can only be allocated to selective deserts; (5) special cultural significance of deserts needs to be acknowledged; and (6) deserts have important roles in global material, energy, and water cycles that need to be better understood before massive alterations are implemented. In short, desertification control should prioritize addressing human-induced desertification rather than attempting to convert all natural deserts into different ecosystems. Desert conservation is also essential to sustainable desert management.

Desert conservation and combatting desertification are not mutually exclusive but complementary to each other. For example, combatting desertification may involve restoration of native desert-adaptive species, benefiting conservation of desert biodiversity. However, desert conservation is less frequently advocated than desertification control. This might be because deserts are often perceived as having limited land productivity, biomass, and human liveability, which can lead to a view that deserts are less important than other types of ecosystems. While there is no widely joined global or regional initiative specific to desert conservation, the Convention on Biological Diversity (CBD), the most influential international convention for nature conservation involving 196 parties, recognizes the significance of diversity of species, genetic sources, and ecosystems, including those associated with deserts (CBD, 2023).

Building protected areas has been a major strategy for conserving nature (CBD, 2020; Hummel et al., 2019), including deserts. Desert protected areas have been established across continents, such as Joshua Tree National Park in the United States, Atacama Desert National Park in Chile, Namib-Naukluft National Park in Namibia, Uluru-Kata Tjuta National Park in Australia, the Lut Desert in Iran, the protected zone of the Tabernas Desert in Spain, and the Antarctic desert regions protected by the Antarctic Treaty. However, desert protected areas are not as common as protected areas for other types of ecosystems (UNEP-WCMC, 2023), although the specific number of global desert protected areas does not have available data. Taking the example of China, the country with the most desert ES valuation studies, only 31 out of its total 2,750 nature reserves are specific for desert conservation (Chinese Ministry of Ecology and Environment, 2018). The Kunming-Montreal Global Biodiversity Framework has committed to improve the coverage of global terrestrial protected areas to 30% (CBD, 2022a) from the current 16.64% (UNEP, 2021b). This creates an opportunity for decision-makers to consider potential expansion and more sustainable management of desert protected areas. This consideration can integrate valuation of desert ES.

5.2. Application of ES valuation for desert management

As exiting desert ES valuation studies are very limited, application of ES valuation for desert management is also limited. In the context of combatting desertification, ES valuation studies have looked at the interaction between changes in ES values and land use changes, including expansion of desertification and converting deserts into other types of lands, such as farmlands and power plants (Fu et al., 2018; Liang and Liu, 2017; Mamat et al., 2021; Peng et al., 2010; Sawut et al., 2013; Taylor et al., 2017). These studies can inform decision-makers about the ES values of alternative land use scenarios and restoration options. They may also inform decision makers about managing desert ecosystems to prevent desert-related natural disasters, especially sandstorms.

In the context of desert conservation, valuing desert ES can highlight the importance of desert landscapes and resources, thereby motivating conservation and arguing for addressing negative environmental impacts from human activities, such as mining and power plant construction that may damage habitats, geodiversity, biodiversity, and landscapes (Jordaan et al., 2021; Murdoch et al., 2017).

Payment for ecosystem services (PES) schemes have been developed worldwide to pay for conserving and enhancing target ES and can be a crucial approach to both combatting desertification and conserving deserts. ES valuation is crucial to implement PES schemes for desert management because ES valuation can raise awareness of both overlooked important deserts and impacts of human-induced desertification, motivate investment for both desert conservation and combatting desertification, and assist with designing payment amounts. Payment amount in theory can be the value of additional ES or the cost of taking actions to maintain or provide target ES (Chen, 2020b). Value-based payment obviously requires ES valuation. While opportunity cost-based payment is more common in practice (Liu et al., 2010) and does not need ES valuation to determine payment amounts, ES valuation still enables researchers to conduct cost-benefit analysis (to determine if the benefits from a PES project outweigh the payment) or cost-effectiveness assessment (that seeks the intervention with the minimum relative costs of achieving per unit of outcomes from multiple alternative interventions) (Chen et al., 2023; UNEP, 2019).

Existing PES projects for desert management focus on paying (or making compensation) for restoring degraded lands or converting deserts into green ecosystems (Huang et al., 2018; Li et al., 2015b; Wang et al., 2023). While evidence shows some people are willing to pay for conservation of deserts (Taylor et al., 2017), PES projects for this purpose was not found in existing studies. This may be due to the ignorance or underestimate of deserts' contributions to people and the planet. For future desert management, PES projects may not only need to cover conservation of a larger area of important deserts, but also can be extended to common asset trusts (CATs) as explained below.

5.3. Extending payment for ecosystem services to common asset trusts

PES is often considered as a voluntary transaction where well-defined ES (or a land use likely to secure the ES) are being 'bought' by a (minimum one) service buyer from a (minimum one) service provider if and only if the service provider secures ES provision (conditionality) (Wunder, 2005). However, Wunder's criteria may be inappropriate because: (1) while private goods may be amenable to voluntary payments, many ES are public or common goods. Few economists call for voluntary payments for public good services (e.g., fire departments, and national defence) (Koellner et al., 2010; Pagiola et al., 2007). Instead, PES may also need government-led approaches. (2) Measuring the benefits of common and public ES to individuals is difficult and costly. (3) As ES may be too complex to be defined precisely, paying for more explicitly defined ES may have higher transaction costs (Rørstad et al., 2007). (4) Schemes that pay for a set of loosely defined ES may still improve social benefits (Porras et al., 2008). (5) Strict conditionality (e.g., monitoring conservation activities) may increase transaction costs substantially and reduce intrinsic motivation to do the right thing for societal wellbeing (Falk and Kosfeld, 2006; Vatn, 2010).

This does not mean that financial incentives are not effective, but they must be used in an institutional and cultural framework based on the goal of managing natural capital for the benefit of all, rather than merely maximizing the value of market exchanges. Economic institutions can be changed but the complex biophysical characteristics of ES cannot (Farley and Costanza, 2010). Therefore, the definition of PES has been extended to be "a transfer of resources between social actors, which aims to create incentives to align individual and/or collective land use decisions with the social interest in the management of natural resources" (Muradian et al., 2010). PES in this broader sense includes most of the influential payment schemes worldwide, including Costa Rica's pathbreaking scheme and China's eco-compensation scheme. China's scheme may involve government-led payments from a higher level of government to a lower level of government to protect ES (without necessarily defining ES explicitly) and to compensate individuals whose livelihoods are impacted by ES conservation (e.g., restricted farming) (General Office of the CCP Central Office and General Office of the State Council of China, 2021). CATs also fall into the broader sense of PES and seek to provide a more participatory, co-produced framework for providing economic incentives for the conservation of natural capital.

Trusts denote legal mechanisms designed to protect and manage assets on behalf of specific beneficiaries and have been used widely across the world. Trusts for ecosystem management integrate the public trust doctrine, community property rights, and a shared purpose (Costanza et al., 2021). CATs in essence are a collection of agreements and polycentrically governed institutions that extend the idea of trusts to the sustainable management and protection of public goods and natural capital, such as the atmosphere, oceans, and ecosystems more broadly. Effective CATs should follow Elinore Ostrom's eight core design principles for sustainable management of common resources. Although CATs and Ostrom's principles are not specific to desert management, they are potentially applicable to deserts.

We did not find any real-world CATs managing desert ES, but examples of a few existing institutions at various scales around the world that are similar to CATs, incorporate at least some of Ostrom's 8 design principles, and manage ES of other types of ecosystems can be found in Costanza et al. (2021). Under a desert CAT, the trustees (e.g., governments, delegated authorities of the governments, or authorized organizations), based on agreements with appointors (desert ES investors, who can be the same as or different from the beneficiaries), have clear legal obligations to manage an asset (including management of land uses, conservation of natural resources and biodiversity, and maintenance of ES of deserts in this context) on behalf of the beneficiaries (e.g., communities living in deserts or the public who hold a stake of deserts) and to distribute benefits (e.g., desert ES) to the beneficiaries as dividends. Moreover, CATs should include conflict resolution procedures, mandatory rules, clear objectives, permission, flexibility for voluntary investments (e.g., in one or multiple ES), and economic mechanisms for promoting sustainable land and resource uses (Canning et al. 2021).

New methods for modelling, measuring, and valuing ES make applications of CATs feasible and also facilitate better public–private partnerships (Costanza et al., 2021). A more nuanced balance of private, public, and community property rights and responsibilities is crucial to ES management. CATs based on Ostrom's 8 core principles can help design and implement this more balanced approach at a range of spatial scales.

6. Suggestions and conclusion

Further research on desert ES is needed, given the notable scarcity of literature, particularly in terms of valuation studies, across the globe. This gap must be addressed, especially in countries with extensive desert regions. Boosting such research is not only vital due to the irreplaceable roles deserts play in global ecosystems, but it is also feasible through a combination of the following approaches. These approaches encompass (1) raising awareness and fostering a more comprehensive view of biodiversity, ES, geodiversity, and values of deserts. This helps to generate interest across a broader scientific community and mobilize support from a diverse array of stakeholders, including the general public, desert managers, decision-makers, and corporate entities; (2) enhancing funding for desert research through mobilizing financial resources from governments, multilateral institutions, and private sectors, as well as through redirecting financial flows away from activities that exacerbate land degradation or harm desert resources towards initiatives that promote sustainable desert management; (3) enhancing other research resources, such as human resources, research equipment, and especially specialized knowledge and tools tailored to adapt the unique issues and characteristics of deserts, through collaborative efforts among stakeholders; and (4) directing valuation research towards policy-making, administrative requirements, and stakeholder preferences to enhance the practical application of research findings in real-world situations.

A more comprehensive understanding of how deserts interact with both people and the planet necessitates further research into the unique species, the special ecological and geological functions of deserts, and their effects on global ES. Potential research may explore the connections between desert health and human health and investigate several functions of sands, including water condensation, biogeochemical cycles, rain acidity neutralization, seed banks, and cultural significance, all of which can impact the wellbeing of humans and other species. Results from these studies are crucial information for sustainable decision-making regarding land and resource management in desert regions, helping to balance desert conservation with efforts to combat desertification and drought and ultimately balance the benefits provided by deserts with those of other ecosystems.

We need not only more valuation studies but also improved quality of valuation. Given the diverse ways people perceive and relate to deserts, it's essential to consider plural perspectives to express values. This means considering various valuation approaches and units. Besides quantitative assessments involving biophysical and monetary units, or rating and ranking of ES, values can also be expressed using qualitative descriptors. Qualitative descriptors include love and respect for deserts, cultural meaning of species, physiological and mental effects (e.g., feeling great) of being in deserts, the right for unique species to live, and other species as co-inhabitants of deserts (IPBES, 2022).

In terms of economic valuation, valuation methods can be more credible and sophisticated through integrating (1) non-linearity between ES quantities and ES values, (2) ES synergies and trade-offs, (3) species identities and traits, (4) fairness and collective knowledge of ES through deliberation (Kenter et al., 2011; Orchard-Webb et al., 2016), (5) dynamic modelling approaches that can quantify potential shifts in ES under different social-economic and environmental scenarios (Costanza, 2020; Kubiszewski et al., 2017), and (6) non-use and option values through conducting practical stated-preference approaches. The legitimacy and credibility of valuation is the basis of the feasibility and reliability of its policy implications.

In the context of deserts, PES schemes are often integrated into the process of combating desertification, instead of conserving important deserts. Valuation of desert ES is crucial to fill this gap through raising awareness of overlooked deserts, motivating investment, designing payment amounts, or estimating the effectivenss of payments. Market-based voluntary PES schemes are not sufficient for managing ecosystems due to the difficulty in measuring explicitly defined ES as well as contributions of common and public ES to individuals. CATs designed according to Ostrom's 8 core principles may benefit sustainable management of deserts (and other ecosystems) based on maintaining the health and value of the whole ecosystems, using economic and other incentives and disincentives. Valuation of desert ES is an essential element to guide management decisions within this structure (See summary in Fig. 6).

CRediT authorship contribution statement

Haojie Chen: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Robert Costanza:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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

No data was used for the research described in the article.

Acknowledgement

This research is funded in part by the Asian Development Bank. This research is also in part supported by a research program administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Department of Agriculture. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of any institute. We thank the journal editor and two anonymous reviewers for their valuable comments on earlier drafts.

References

Chinese Academy of Forestry, 2012. Assessment Standards of Desert Ecosystem Services.
ADB, 2005. Technical Assistance for Central Asian Countries Initiative for Land Management (Cofinanced by the Global Environment Facility and the Global Mechanism).
Addas, A., 2022. Exploring the pattern of use and accessibility of urban green spaces: Evidence from a coastal desert megacity in Saudi Arabia. Environ. Sci. Pollut. Res. 29, 55757–55774.
Alsharif, W., Saad, M.M., Hirt, H., 2020. Desert microbes for boosting sustainable agriculture in extreme environments. Front. Microbiol. 11, 496411.
Aragón-Gastélum, J.L., Flores, J., Jurado, E., Ramírez-Tobías, H.M., Robles-Díaz, E., Rodas-Ortiz, J.P., Yáñez-Espinosa, L.J.S.S.R., 2018. Potential impact of global warming on seed bank, dormancy and germination of three succulent species from the Chihuahuan Desert. 28, 312-318.
Aziz, T., 2021. Changes in land use and ecosystem services values in Pakistan, 1950–2050. Environmental Development 37, 100576.
Baddock, M., Boskovic, L., Strong, C., McTainsh, G., Bullard, J., Agranovski, I., Cropp, R., 2013. Iron-rich nanoparticles formed by aeolian abrasion of desert dune sand. Geochem. Geophys. Geosyst. 14, 3720–3729.
Bahari, A., Azami, S., Goudarztalejerdi, A., Karimi, S., Esmaeili, S., Chomel, B.B., Sazmand, A., 2021. Zoonotic Disease: Molecular Detection of Zoonotic Pathogens in the Blood and Tissues of Camels (Camelus dromedarius) in Central Desert of Iran. Yale Journal of Biology Medicine 94, 249.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.
Bishop, R.C., Champ, P.A., Brown, T.C., McCollum, D.W., 1997. Measuring non-use values: theory and empirical applications, Determining the Value of Non-Marketed Goods. Springer, pp. 59-81.
Bremer, L.L., Farley, K.A., 2010. Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. Biodivers. Conserv. 19, 3893–3915.
CACILM, 2016. Sustainable land management in Central Asia: Achievements at a glance.
CBD, 2020. Global Biodiversity Outlook 5. Secretariat of the Convention on Biological Diversity, Montreal, Canada.
CBD, 2022a. COP15: Final text of Kunming-Montreal Global Biodiversity Framework.
CBD, 2022b. Final text of Kunming-Montreal Global Biodiversity Framework available in all languages. Convention on Biological Diversity, Montreal, Canada.
CBD, 2023. Biodiversity. Convention on Biological Diversity.
Chan, K.M.A., Goldstein, J., Satterfield, T., Hannahs, N., Kikiloi, K., Naidoo, R., Vadeboncoeur, N., Woodside, U., 2011. Cultural services and non-use values. In: Kareiva, P., Tallis, H., Rickets, T.H., Daily, G.C., Polaksy, S. (Eds.), Natural Capital: Theory and Practice of Mapping Ecosystem Services. Oxford University Press, Oxford, UK, pp. 206–228.
Chen, H., 2020a. Complementing conventional environmental impact assessments of tourism with ecosystem service valuation: A case study of the Wulingyuan Scenic Area, China. Ecosystem Services 43, 101100.
Chen, H., 2020b. Land use trade-offs associated with protected areas in China: Current state, existing evaluation methods, and future application of ecosystem service valuation. Sci. Total Environ. 711, 134688.

Chen, H., Costanza, R., Kubiszewski, I., 2022. Land use trade-offs in China's protected areas from the perspective of accounting values of ecosystem services. J. Environ. Manage. 315, 115178.
Chen, H., Zhang, T., Costanza, R., Kubiszewski, I., 2023. Review of the approaches for assessing protected areas' effectiveness. Environ. Impact Assess. Rev. 98, 106929.
Cheng, L., Guo, H., Lu, Q., 2013. Review on the valuation of desert ecosystem service values. J. Desert Res. 33, 281–287.
Cheng, L., Yang, L., Yao, X., Lu, Q., 2020. China's Desert Ecosystem: Functions Rising and Services Enhancing. Bulletin of Chinese Academy of Sciences 35, 690–698.
Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., von Maltitz, G., 2018. World Atlas of Desertification. Publication Office of the European Union, Luxembourg.
Chinese Central Government, 2023. Over 67% of the Coutry's desertified land will be treated by 2030.
Chinese Ministry of Ecology and Environment, 2018. Nature and Ecology. Bulletin of Natural Environment Status of China 37–40.
Chinese Ministry of Ecology and Environment, 2020. Building a Shared Future for All Life on Earth: China in Action, pp. 1-26.
Cioruța, B.-V., Coman, M., 2020. Global Desert Areas Vs Local Mining Areas from Maramure? County (Romania). Asian Journal of Geographical Research 45–52.
Costanza, R., 2020. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. Ecosyst. Serv. 43, 101096.
Costanza, R., de Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158.
Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosyst. Serv. 28, 1–16.
Costanza, R., Atkins, P.W., Hernandez-Blanco, M., Kubiszewski, I., 2021. Common asset trusts to effectively steward natural capital and ecosystem services at multiple scales. J. Environ. Manage. 280, 111801.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., Raskin, R.G., 1997a. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Naeem, S., Limburg, K., Paruelo, J., O'Neill, R.V., Raskin, R., Sutton, P., M., v.d.B., 1997b. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.
Cuni-Sanchez, A., Pfeifer, M., Marchant, R., Burgess, N.D.J.E.S., 2016. Ethnic and locational differences in ecosystem service values: Insights from the communities in forest islands in the desert. 19, 42-50.
Dagvadorj, D., Natsagdorj, L., Dorjpurev, J., Namkhainyam, B., 2009. Mongolia: Assessment Report on Climate Change 2009. Mongolia Ministry of Environment, Nature and Tourism, Ulaanbaatar, Mongolia.
Davies, J., Campbell, D., Campbell, M., Douglas, J., Hueneke, H., LaFlamme, M., Pearson, D., Preuss, K., Walker, J., Walsh, F., 2011. Attention to four key principles can promote health outcomes from desert Aboriginal land management. The Rangeland Journal 33, 417–431.
de Groot, R., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272.
de Groot, R., Brander, L., Van Der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., Ten Brink, P., Van Beukering, P., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61.
Dodds, W.K., Wilson, K.C., Rehmeier, R.L., Knight, G.L., Wiggam, S., Falke, J.A., Dalgleish, H.J., Bertrand, K.N., 2008. Comparing ecosystem goods and services provided by restored and native lands. Bioscience 58, 837–845.
Durant, S., Pettorelli, N., Bashir, S., Woodroffe, R., Wacher, T., De Ornellas, P., Ransom, C., Abáigar, T., Abdelgadir, M., El Alqamy, H., 2012. Forgotten biodiversity in desert ecosystems. Science 336, 1379–1380.
Falk, A., Kosfeld, M., 2006. The hidden costs of control. Am. Econ. Rev. 96, 1611–1630.
Farber, S., Costanza, R., Childers, D.L., Erickson, J., Gross, K., Grove, M., Hopkinson, C. S., Kahn, J., Pincetl, S., Troy, A., 2006. Linking ecology and economics for ecosystem management. Bioscience 56, 121–133.
Farley, J., 2012. Ecosystem services: The economics debate. Ecosyst. Serv. 1, 40–49.
Farley, J., Costanza, R., 2010. Payments for ecosystem services: From local to global. Ecol. Econ. 69, 2060–2068.
Fu, Q., Hou, Y., Wang, B., Bi, X., Li, B., Zhang, X., 2018. Scenario analysis of ecosystem service changes and interactions in a mountain-oasis-desert system: a case study in Altay Prefecture, China. Sci. Rep. 8, 1–13.
Gehlot, H.S., Tak, N., Dagla, H.R., Davis, T.D., 2014. Indigenous and modern scientific strategies for characterization, conservation and sustainable utilization of bio-resources of the Indian Thar Desert. Journal of Arid Land Studies 24, 5–8.
General Office of the CCP Central Office, General Office of the State Council of China, 2021. Advice on Furhter Reforming the Systems of Eco-compensation.
National Geographic, 2023a. Desert Biome.
National Geographic, 2023b. Deserts expalined.
Haight, J.D., Reed, S.C., Faist, A.M., 2019. Seed bank community and soil texture relationships in a cold desert. J. Arid Environ. 164, 46–52.
Hansen, M.H., Li, H., Svarverud, R., 2018. Ecological civilization: Interpreting the Chinese past, projecting the global future. Glob. Environ. Chang. 53, 195–203.
Hernández-Blanco, M., Costanza, R., Chen, H., DeGroot, D., Jarvis, D., Kubiszewski, I., Montoya, J., Sangha, K., Stoeckl, N., Turner, K., 2022. Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. Glob. Chang. Biol.
Huang, L., Shao, Q., Liu, J., Lu, Q., 2018. Improving ecological conservation and restoration through payment for ecosystem services in Northeastern Tibetan Plateau, China. Ecosyst. Serv. 31, 181–193.
Hummel, C., Poursanidis, D., Orenstein, D., Elliott, M., Adamescu, M.C., Cazacu, C., Ziv, G., Chrysoulakis, N., van der Meer, J., Hummel, H., 2019. Protected Area management: Fusion and confusion with the ecosystem services approach. Sci. Total Environ. 651, 2432–2443.
Iknayan, K.J., Beissinger, S., 2018. Collapse of a desert bird community over the past century driven by climate change. Proceedings of the National Academy of Sciences 115, 8597-8602.
IPBES, 2022. Methodological assessment regarding the diverse conceptualization of multiple values of nature and its benefits, including biodiversity and ecosystem functions and services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
IUCN, 2012. IUCN habitat classification scheme.
Jasper, D., 2008. The sacred desert: Religion, literature, art, and culture. John Wiley & Sons.
Jiang, C., Wang, D., Luo, S., Li, D., Zhang, L., Gao, Y., 2017. Ecosystem status changes and attribution in the three-river headwaters region. Res. Environ. Sci. 30, 10–19.
Johnston, R.J., Boyle, K.J., Adamowicz, W., Bennett, J., Brouwer, R., Cameron, T.A., Hanemann, W.M., Hanley, N., Ryan, M., Scarpa, R., 2017. Contemporary guidance for stated preference studies. J. Assoc. Environ. Resour. Econ. 4, 319–405.
Jordaan, S.M., Lee, J., McClung, M.R., Moran, M.D., 2021. Quantifying the ecosystem services values of electricity generation in the US Chihuahuan Desert: A life cycle perspective. J. Ind. Ecol.
Kassegn, A., Endris, E., 2021. Review on socio-economic impacts of 'Triple Threats' of COVID-19, desert locusts, and floods in East Africa: Evidence from Ethiopia. Cogent Social Sciences 7, 1885122.
Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Kingsford, R.T., 2020. The IUCN Global Ecosystem Typology 2.0: Descriptive profiles for biomes and ecosystem functional groups. IUCN, Gland, Switzerland.
Kenter, J.O., Hyde, T., Christie, M., Fazey, I., 2011. The importance of deliberation in valuing ecosystem services in developing countries—evidence from the Solomon Islands. Glob. Environ. Chang. 21, 505–521.
Koellner, T., Sell, J., Navarro, G., 2010. Why and how much are firms willing to invest in ecosystem services from tropical forests? A comparison of international and Costa Rican firms. Ecol. Econ. 69, 2127–2139.
Kong, Z.-H., Stringer, L., Paavola, J., Lu, Q., 2021. Situating China in the global effort to combat desertification. Land 10, 702.
Kroeger, T., Manalo, P., 2007. Economic benefits provided by natural lands: Case study of California's Mojave Desert. Defenders of Wildlife, Washington, DC.
Kubiszewski, I., Costanza, R., Anderson, S., Sutton, P., 2017. The future value of ecosystem services: Global scenarios and national implications. Ecosyst. Serv. 26, 289–301.
Kubiszewski, I., Muthee, K., Rasheed, A.R., Costanza, R., Suzuki, M., Noel, S., Schauer, M., 2022. The costs of increasing precision for ecosystem services valuation studies. Ecol. Ind. 135, 108551.
Li, Y., Fan, M., Li, W., 2015b. Application of payment for ecosystem services in China's rangeland conservation initiatives: a social-ecological system perspective. The Rangeland Journal 37, 285–296.
Li, X., Li, M., Dong, S., Shi, J., 2015a. Temporal-spatial changes in ecosystem services and implications for the conservation of alpine rangelands on the Qinghai-Tibetan Plateau. The Rangeland Journal 37, 31–43.
Liang, Y., Liu, L., 2017. An integrated ecosystem service assessment in an artificial desert oasis of northwestern China. J. Land Use Sci. 12, 154–167.
Liu, S., Costanza, R., Farber, S., Troy, A., 2010. Valuing ecosystem services: theory, practice, and the need for a transdisciplinary synthesis. Ann. N. Y. Acad. Sci. 1185, 54–78.
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., 2007. Complexity of coupled human and natural systems. Science 317, 1513–1516.
Lortie, C.J., Braun, J., Westphal, M., Noble, T., Zuliani, M., Nix, E., Ghazian, N., Owen, M., Butterfield, H.S., 2020. Shrub and vegetation cover predict resource selection use by an endangered species of desert lizard. Sci. Rep. 10, 1–7.
Ma, G., Yu, F., Wang, J., Zhou, X., Yuan, J., Mou, X., Zhou, Y., Yang, W., Peng, F., 2017. Measuring gross ecosystem product (GEP) of 2015 for terrestrial ecosystems in China. China Environ. Sci. 37, 1474–1482.
Magalhaes, A., 2017. Towards National Droght Policeis in Latin American and the Caribbean Region. United Nations Convention on Combatting Desertification, Bonn, Germany.
Mamat, A., Wang, J., Ma, Y., 2021. Impacts of Land-Use Change on Ecosystem Service Value of Mountain–Oasis–Desert Ecosystem: A Case Study of Kaidu-Kongque River Basin, Northwest China. Sustainability 13, 140.
Marre, J.-B., Brander, L., Thebaud, O., Boncoeur, J., Pascoe, S., Coglan, L., Pascal, N., 2015. Non-market use and non-use values for preserving ecosystem services over time: A choice experiment application to coral reef ecosystems in New Caledonia. Ocean Coast. Manag. 105, 1–14.
Martínez-Valderrama, J., Guirado, E., Maestre, F.T., 2020. Desertifying Deserts. Nature Sustainability 3, 572–575.
Millennium Ecosystem Assessment, 2005. Ecosystems and human well-being: current state and trends. Washington, DC (USA) Island Press.
Muradian, R., Corbera, E., Pascual, U., Kosoy, N., May, P.H., 2010. Reconciling theory and practice: An alternative conceptual framework for understanding payments for environmental services. Ecol. Econ. 69, 1202–1208.

Murdoch, J.D., Reading, R.P., Amgalanbaatar, S., Wingard, G., Lkhagvasuren, B., 2017. Ecological interactions shape the distribution of a cultural ecosystem service: Argali sheep (Ovis ammon) in the Gobi-Steppe of Mongolia. Biol. Conserv. 209, 315–322.
Niu, S.-W., Li, Y.-H., Ma, L.-B., Sun, H.-J., 2009. Evaluate the importance of ecosystem in major function zoning of gansu province. China Popul. Resour. Environ. 19, 119–124.
Orchard-Webb, J., Kenter, J.O., Bryce, R., Church, A., 2016. Deliberative democratic monetary valuation to implement the ecosystems approach. Ecosyst. Serv. 21, 308–318.
Ouyang, Z., Song, C., Zheng, H., Polasky, S., Xiao, Y., Bateman, I.J., Liu, J., Ruckelshaus, M., Shi, F., Xiao, Y., 2020. Using gross ecosystem product (GEP) to value nature in decision making. Proceedings of the National Academy of Sciences 117, 14593-14601.
Pagiola, S., Ramírez, E., Gobbi, J., De Haan, C., Ibrahim, M., Murgueitio, E., Ruíz, J.P., 2007. Paying for the environmental services of silvopastoral practices in Nicaragua. Ecol. Econ. 64, 374–385.
Pascual, U., Balvanera, P., Anderson, C.B., Chaplin-Kramer, R., Christie, M., González-Jiménez, D., Martin, A., Raymond, C.M., Termansen, M., Vatn, A., 2023. Diverse values of nature for sustainability. Nature 1–11.
Peng, J., Zhuo, Y., An, W., Shi, Q., 2010. Assessment on functional value of ecosystem service in oasis and desert criss-cross zone in Qitai region. Xinjiang Agricultural Sciences 47, 1665–1670.
Porras, I.T., Grieg-Gran, M., Neves, N., 2008. All that glitters: A review of payments for watershed services in developing countries.
Richardson, R.B., 2005. The economic benefits of California desert wildlands: 10 years since the California Desert Protection Act of 1994. The Wilderness Society: Washington, DC, USA.
Rørstad, P.K., Vatn, A., Kvakkestad, V., 2007. Why do transaction costs of agricultural policies vary? Agric. Econ. 36, 1–11.
Sagie, H., Morris, A., Rofè, Y., Orenstein, D.E., Groner, E., 2013. Cross-cultural perceptions of ecosystem services: A social inquiry on both sides of the Israeli-Jordanian border of the Southern Arava Valley Desert. J. Arid Environ. 97, 38–48.
Salguero-Gomez, R., Siewert, W., Casper, B.B., Tielbörger, K., 2012. A demographic approach to study effects of climate change in desert plants. Philos. Trans. R. Soc., B 367, 3100–3114.
Sawut, M., Eziz, M., Tiyip, T., 2013. The effects of land-use change on ecosystem service value of desert oasis: a case study in Ugan-Kuqa River Delta Oasis, China. Can. J. Soil Sci. 93, 99–108.
Schild, J.E., Vermaat, J.E., van Bodegom, P.M., 2018. Differential effects of valuation method and ecosystem type on the monetary valuation of dryland ecosystem services: A quantitative analysis. J. Arid Environ. 159, 11–21.
Sinamai, A., 2017. Myths as metaphors: understanding narratives in sustaining sacred landscapes in Zimbabwe and Australia. In: Munyaradzi, M., Shadreck, C. (Eds.), Archives, Objects, Places and Landscapes: Multidisciplinary Approaches to Decolonised Zimbabwean Pasts. Langaa Research & Publishing CIG, Mankon, Bamenda, pp. 399–419.
Stosch, K.C., Quilliam, R.S., Bunnefeld, N., Oliver, D.M., 2019. Quantifying stakeholder understanding of an ecosystem service trade-off. Sci. Total Environ. 651, 2524–2534.
Taylor, N.T., Davis, K.M., Abad, H., McClung, M.R., Moran, M.D., 2017. Ecosystem services of the Big Bend region of the Chihuahuan Desert. Ecosyst. Serv. 27, 48–57.
Terada, H., Ueda, H., Wang, Z., 2002. Trend of acid rain and neutralization by yellow sand in east Asia—a numerical study. Atmos. Environ. 36, 503–509.
Turner, R., Daily, G., 2008. The ecosystem services framework and natural capital conservation. Environ. Resour. Econ. 39, 25–35.
Unccd, 2023. Funding institutions. United Nations Convention on Combatting Desertification.
UNCCD, 2017c. The future strategic framework of the Convention.
UNCCD, 2017a. About the convention.
UNCCD, 2017b. Central Asian countries ready to start second phase of ambitious regional SLM programme.
UNCCD, 2020. The Great Green Wall Initiative.
UNCCD, 2021. About the convention.
Unep, 2006. Global Desert Outlook. United Nations Environment Programme, Narobi, Kenya.
Unep, 2015. Review of the Kubuqi Ecological Restoration Project: A Desert Green Economy Pilot Initiative. United Nations Environment Programme, Nairobi, Kenya.
Unep, 2019. Guidelines for Conducting Integrated Environmental Assessments. United Nations Environment Programme Nairobi, Kenya.
UNEP, 2021a. UNEP launches a virtual journey through three unique desert ecosystems.
UNEP, 2021b. World met target for protected area coverage on land, but quality must improve.
UNEP-WCMC, 2023. Protected planet. United Nations Environment Programme World Conservation Monitoring Centre.
United Nations SEEA-EA, 2021. System of Environmental-Economic Accounting—Ecosystem Accounting. White cover publication.
United Nations, 2010. United Nations Decade for Deserts and the Fight against Desertification.
Vatn, A., 2010. An institutional analysis of payments for environmental services. Ecol. Econ. 69, 1245–1252.
Venable, D.L., Flores-Martinez, A., Muller-Landau, H.C., Barron-Gafford, G., Becerra, J. X., 2008. Seed dispersal of desert annuals. Ecology 89, 2218–2227.
Wang, J.-Y., Gao, C.-H., Yang, Y.-T., Chen, H.-T., Zhu, X.-H., Lv, S., Chen, S.-B., Tong, S.-X., Steinmann, P., Ziegelbauer, K., 2010. An outbreak of the desert sub-type of zoonotic visceral leishmaniasis in Jiashi, Xinjiang Uygur Autonomous Region, People's Republic of China. Parasitol. Int. 59, 331–337.
Wang, X., Ge, Q., Geng, X., Wang, Z., Gao, L., Bryan, B.A., Chen, S., Su, Y., Cai, D., Ye, J., 2023. Unintended consequences of combating desertification in China. Nat. Commun. 14, 1139.
Wei, L., Zhou, L., Sun, D., Yuan, B., Hu, F., 2022. Evaluating the impact of urban expansion on the habitat quality and constructing ecological security patterns: A case study of Jiziwan in the Yellow River Basin. China. Ecological Indicators 145, 109544.
World Health Organization, 2015. Biodiversity and Health.
Wunder, S., 2005. Payments for environmental services: some nuts and bolts.
Xu, Z., Elomri, A., El Omri, A., Kerbache, L., Liu, H., 2021. The compounded effects of COVID-19 pandemic and desert locust outbreak on food security and food supply chain. Sustainability 13, 1063.
Yan, X., Li, L., 2023. Spatiotemporal characteristics and influencing factors of ecosystem services in Central Asia. J. Arid. Land 15, 1–19.
Yao, Z., 2020. Deserts are a special type of ecosystem, China Green Time.
Zastrow, M., 2019. China's tree-planting could falter in a warming world. Nature 573, 474–475.
Zhai, Y., Jiang, Y., Cao, X., Leng, S., Wang, J., 2022. Valuation of ecosystem damage induced by soil-groundwater pollution in an arid climate area: framework, method and case study. Environ. Res. 211, 113013.
Zhang, T., Chen, Y., 2022. The effects of landscape change on habitat quality in arid desert areas based on future scenarios: Tarim River Basin as a case study. Front. Plant Sci. 13, 1031859.
Zhao, H., Guo, B., Wang, G., 2023. Spatial-Temporal Changes and Prediction of Carbon Storage in the Tibetan Plateau Based on PLUS-InVEST Model. Forests 14, 1352.
Zhou, J., Zhao, Y., Huang, P., Zhao, X., Feng, W., Li, Q., Xue, D., Dou, J., Shi, W., Wei, W., 2020. Impacts of ecological restoration projects on the ecosystem carbon storage of inland river basin in arid area. China. Ecological Indicators 118, 106803.
Zhu, G., Qiu, D., Zhang, Z., Sang, L., Liu, Y., Wang, L., Zhao, K., Ma, H., Xu, Y., Wan, Q., 2021. Land-use changes lead to a decrease in carbon storage in arid region, China. Ecological Indicators 127, 107770.
Zou, Z., Wu, T., Xiao, Y., Song, C., Wang, K., Ouyang, Z., 2020. Valuing natural capital amidst rapid urbanization: assessing the gross ecosystem product (GEP) of China's 'Chang-Zhu-Tan'megacity. Environ. Res. Lett. 15, 124019.