Challenges and solutions to biodiversity conservation in Arid lands

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Abstract

The strategic goals of the United Nations and the Aichi Targets for biodiversity conservation have not been met. Instead, biodiversity has continued to rapidly decrease, especially in developing countries. Setting a new global biodiversity framework requires clarifying future priorities and strategies to bridge challenges and provide representative solutions. Hyper-arid, arid, and semi-arid lands (herein, arid lands) form about one third of the Earth's terrestrial surface. Arid lands contain unique biological and cultural diversity, and biodiversity loss in arid lands can have a disproportionate impact on the ecosystem due to low redundancy and a high risk of trophic cascades. They contain unique biological and cultural diversity and host many endemic species, including wild relatives of key crop plants. Yet extensive agriculture, unsustainable use, and global climate change are causing an irrecoverable damage to arid lands, with far-reaching consequences to the species, ground-water resources, ecosystem productivity, and ultimately the communities' dependant on these systems. However, adequate research and effective policies to protect arid land biodiversity and sustainability are lacking because a large proportion of arid areas are in developing countries, and the unique diversity in these systems is frequently overlooked. Developing new priorities for global arid lands and mechanisms to prevent unsustainable development must become part of public discourse and form the basis for conservation efforts. The current situation demands the combined efforts of researchers, practitioners, policymakers, and local communities to adopt a socio-ecological approach for achieving sustainable development (SDGs) in arid lands. Applying these initiatives globally is imperative to conserve arid lands biodiversity and the critical ecological services they provide for future generations. This perspective provides a framework for conserving biodiversity in arid lands for all stakeholders that will have a tangible impact on sustainable development, nature, and human well-being.

With approximately three quarters of the Earth's land surface and two thirds of its oceans degraded or threatened, biodiversity and ecological integrity are facing unprecedented levels of threat (IPBES, 2019). Despite a series of international agreements intended to reverse this trend, neither extinction risks nor underlying stressors such as climate change have been halted, let alone reversed (Almond et al., 2020). The post-2020 global biodiversity framework will soon be launched, so we have a unique opportunity to revisit how we manage this planet and an urgent need to examine our priorities in the future. This requires careful consideration of *where* we focus future efforts and *what* further data we need to manage these systems effectively. Hyper-diverse ecosystems such as forests and coral reefs have received much attention, but other ecosystems may be overlooked, neglected, or even seen as marginal, despite their importance to a suite of unique species and human cultures including medical, cultural, food and spiritual uses (Maestre et al., 2021). For example, hyper-arid, arid and semi-arid landscapes make up nearly a third of the Earth's terrestrial surface and are home to 18.5% of the world's population (Millennium Ecosystem Assessment, 2005). Arid lands are typically defined based on the aridity index, in addition to other metrics such as the dominant vegetation type and climate. Arid lands are generally divided into three main categories; hyper arid zone (arid index <0.3): scant/no vegetation, precipitation <100 mm annually (irregular/infrequent, sometimes droughts last multiple years). Arid zones have 100-150mm moisture per year, and semi-arid 150 to 300 mm per year, dry subhumid systems are sometimes also considered as arid ecosystems (Millennium Ecosystem Assessment, 2005; Cherlet et al., 2018). Within each of these broad types of arid ecosystem are many separate ecoregions, with differing geology, and biogeography, and thus representing unique communities (Maestre et al., 2021; Fig. 1), it should also be noted that definitions do vary and there is not absolute consensus on what constitutes dryland, and any different unique ecoregions within these environments (Gaur et al., 2017; Ulrich et al., 2014). However, these landscapes are frequently perceived as barren, to the extent that they risk being used as targets for various endeavours of afforestation to offset the impacts of climate change (Dregne, 1986; Lezak, 2018). The impact of such strategies is stated to be the major threat to grassland ecosystems, which can be misguidedly converted irrespective of their native biodiversity (Scholtz & Twidwell., 2022). Insufficient research has been conducted to facilitate sustainable management and implement practices to minimize the loss of biodiversity and promote effective conservation in hyperarid, arid and semiarid landscapes (hereafter, arid lands), mainly distributed in central Asia, northern and southern Africa, southern Europe, western North America, western South America, and Australia (Fig. 1).

Arid lands have expanded in recent decades and are expected to further expand in coming decades due to inappropriate management and changing climates (Spinoni et al., 2021), but these drylands should not be confused with the majority of dryland ecosystems which are threatened by mismanagement. They are often viewed as a problem that should be "solved", or a space that can be filled with a more desirable ecosystem, or treated as degraded rather than a diverse ecosystem, and consequently rarely studied in their own right (Feng and Fu, 2013; Yao et al., 2020; Spinoni et al., 2021). Arid regions are characterized by relatively fewer species than the better-watered biomes, but high levels of endemism, and particularly high functional diversity, thus the loss of a species in arid lands represents a percentage of biodiversity loss much higher than in more species-rich regions (McNeely, 2003; Maestre et al., 2021). This makes arid lands a very special regions regarding biodiversity conservation, especially in a climate change scenario where aridity is increasing (Huang et al., 2017). Mentions of arid ecosystems within UN sustainability agendas and SDGs are limited to ecosystem manipulation to prevent desertification, conflating arid lands with degraded systems, and without the distinction between these fragile natural systems and degradation of other ecosystems (UN, 2015), often as the result of agricultural practices (Pacheco et al., 2018). Planting trees in arid ecosystems is considered a solution to environmental degradation and for the mitigation of climate change. Effective panaceas, however, are rare in natural ecosystems, and such an approach is not appropriate for arid lands; however, more data are needed to provide solutions for these systems to recover from degradation (Tölgyesi et al., 2021). These endeavours (such as the Great Green Wall in Africa, and the Billion Tree Tsunami in Pakistan) have the potential to negatively impact native diversity through habitat encroachment, changes to the water-table, negatively impact local wetlands, the spread of invasive species, and even allelopathic properties from the use of certain non-native species (Phelps et al., 2012; Davies, 2017; Bond et al., 2019; Sabir et al., 2020; Ullah et al., 2020; Naia et al., 2021). These initiatives may also have largely economic motivations, and whilst stating there are biodiversity increases, metrics to assess this are rarely included (Sarr et al., 2021), and a clear basis are needed to protect native species from such initiatives. Furthermore, as well as damaging native diversity these endeavours can have a low success rate, with 80% of planted trees dying within two months of being planted (Brove, 2021) in the Great Green Wall in Northern China. Likewise, whilst the FAO has explicit text on sustainable development of arid lands (Malagnoux., 2007; FAO 1989; Sombroek & Sene 1993), it lacks adequate inclusion of biodiversity and focuses more on agriculture than genuine sustainability.

Current status of biodiversity in arid lands

Arid lands host a large proportion of global biodiversity with diverse adaptations to the xeric (arid) conditions, enabling them to survive high temperatures and low moisture. Due to their unique climatic patterns and distribution, these arid lands have nourished rich endemic biological diversity. For example, the mountains of central Asia host over 75% of the species of vascular plants in the region (Zhang et al., 2020) and are one of 36 global hotspots of biodiversity (Myers et al., 2000). This region hosts 9520 recorded species of vascular plants belonging to 138 families and 1176 genera, in which over a tenth - at least 1010 species - are rare and endangered, many with economic, medicinal, dietary, ornamental, and fodder values (Myers et al., 2000; FO, 2015; IUCN, 2015-2016). More than 900 vertebrate species and tentatively over 100,000 species of invertebrates have been documented in the region, but due the lack of systematic research and inventory, regionally endemic species may be lost even before they are formally described (Lazkov, 2016; Li et al., 2020). This loss translates not simply as the loss of species but also as the loss of varieties of crop-progenitors, such as various fruit trees (Lapena et al., 2014). Given the climate range encompassed by arid lands, further research of species adaptations in these regions may provide fundamental insights to facilitate approaches which enable both the maintenance of biodiversity under a changing climate, but also the development of new crop varieties selected to cope with these challenging conditions. The potential for medicine, and food, as well as crucial genetic information make understanding and preserving these species a crucial question for humanity. Yet like the former inland saline lake the Aral Sea, many Arid lands are under threat, and thus more practical measures are needed for their effective protection.

Similarly, about 45% of the landmass in Africa is arid, and 40% of Africa's population lives in dry land areas (Myers et al., 2000). The Horn of Africa has also officially been identified as a biodiversity hotspot (Pimm et al., 2014), and the plant database of tropical eastern Africa includes at least 16,143 species belonging to 248 families and 2,306 genera. A total of 3,000 species are endemic, 700 of them succulent. The second arid biodiversity hotspot in Africa is the Succulent Karoo situated along the west coast of South Africa and Namibia. This region boasts 4849 plant species of which 1940 are endemic (Myers et al., 2000). The Sahara-Sahel region in Africa contains about 2,800 species of vascular plants, one-quarter of which are endemic. The region is home to 1,147 species of terrestrial vertebrates, 79 of which are listed on the IUCN Red List as threatened, and 125 are endemic (Houérou and Henry, 2009; Brito et al., 2016). Other arid lands include some of the Caribbean islands, parts of the Middle East, and areas of North America, Central America, South America, and Australia (Pimm et al., 2014), all of which provide key habitats for a variety of endemic species. Yet despite this diversity, with the exception of reptiles, these regions only have a small percentage of their area with data available for analysis, or reasonable sampling levels relative to their diversity (Hughes et al., 2021). Many arid land species endemic of arid lands are threatened by the progressive degradation and loss of habitats and shifting climates, and consequently 86% of large desert vertebrates are endangered or extinct. For example, desert bird communities have collapsed, with a loss of 43% of species at some sites (Durant et al., 2014; Iknayan et al., 2018).

Why do arid lands matter?

Ecosystem services provided by arid lands are integral to safeguarding human well-being and a host of species dependent upon these unique ecosystems (Kang et al., 2020). Some of these species are essential wild species of crop relatives (such as many fruit trees; Lapena et al., 2014), providing vital genetic resources which may be crucial to food security into the future. Furthermore, deserts and rocky ecosystems have the second largest proportion of critically endangered plants of all ecosystems in global analysis (Hobohm et al., 2021). Conserving the biodiversity of these arid lands is therefore indispensable to achieving global conservation targets, such as those outlined by the Convention on Biological Diversity (CBD).

Arid lands represent diversity hotspots for a range of plant and animal taxa, such as Asteraceae, Poaceae, Aizoaceae, Agavaceae, Cactaceae and Camphomorosmeae, as well as representing the sole refugia formerly more widely distributed taxa such as the monotypic phreatophyte *Welwitschia mirabilis* (with sister taxa deriving from the opening of the opening of the Equatorial Atlantic Gateway 145–100 Ma) and now limited to Kaokoveld Desert between Namibia and Angola (Jacobson & Lester, 2003). Given the wide taxonomic diversity, including ancient lineage diversity within arid ecosystems, conserving these groups is an essential component of global conservation.

Conservation is crucial in these arid lands because they are especially vulnerable to climate change and anthropogenic activities (Lian et al., 2021). Shallow topsoil and variable fertility slow the recovery of these systems and increase their vulnerability to erosion when disturbed (Vetter. 2009). This may convert habitable diverse environments to areas which lose both their biodiversity and economic value of the services and products they provide, as evidenced by various arid lands across the planet (Feng and Fu, 2013; Yao et al., 2020; Spinoni et al., 2021). Preventing the further loss of ecological function in these ecologically fragile regions will require caution to prevent mismanagement creating irreversible shifts in access to water, and the loss of all species dependent upon these systems. As demonstrated from the collapse of the various desert lakes such as the Aral-sea, the decline of Lake Chad (in Central Africa) and other saline lakes (Gao et al., 2011; Wurtsbaugh et al., 2017), changes in these regions can directly alter the water-table and desert aquifers and lead to transformation of the ecosystem, and thus the resources previously provided by the system. Similar evidence exists from former habitation in desertified parts of China and other regions where changes in climate relating to unsustainable water use and inappropriate management have rendered the areas uninhabitable (Feng et al., 2015). Mismanagement can lead to soil salinization (reducing long term productivity), and enable the spread of invasive pests and pathogens which may spread with the introduction of non-native species (such as livestock), yet the control of invasive species can cost billions of dollars annually (Diagne et al., 2020; Kourantidou et al., 2021). Ultimately these impacts lead to the loss of biodiversity and the economic value, which is specially concerning taking into account that globally, the human population in arid areas is projected to increase from approximately 1.4 billion in 1981-2010 up to 4.4 billion by 2100 (Spinoni et al., 2021).

Main threats to the conservation of biodiversity in arid lands

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019 Global Assessment Report on Biodiversity and Ecosystem Services highlighted that biodiversity in arid lands has been lost in the last century at a rate not seen since the last mass extinction 66 million years ago (IPBES, 2019; Gingerich, 2020). The strategic plan (2011-2020) of the United Nations and the Aichi Targets for halting the loss of biodiversity and ensuring ecosystem resilience has not been met (Green et al., 2019). This under-achievement of targets is especially acute in developing countries in Africa and central Asia, likely in part due to a lack of prioritisation or resources, so urgent steps are needed to safeguard biodiversity in ecologically fragile regions, as less diverse ecosystems such as arid systems are often overlooked. Various factors are driving the loss of biodiversity, and whilst the overarching themes may be cross-cutting across ecosystems (such as agriculture) how it manifests in frequently water limited systems with high endemism is specific to arid systems, and all forms of threat require sensitive and targeted actions as detailed below:

Agriculture

Rapid population growth and expansion of farmland have overdrawn water resources, leading to the degradation of ecosystems and the loss of species in arid lands. There are multiple worrying examples. Encroachment in arid and semi-arid ecosystems such as the Chaco in South America for cattle-ranching has continued to reduce these unique habitats, which decreases the suitability for various species that have small microclimates and shifts the plant community to one dominated by less palatable generalist plants (Silcock and Fensham, 2019; Cordier et al., 2021), as well as directly destroying natural habitats and threatening the survival of species.

The Aral Sea (in Central Asia) is one of the largest inland lakes on earth, but lost of 90% of water surface area in the last few decades, and is an example of the sensitivity to irreversible harm due to mismanagement, which stemmed from the diversion of water for agricultural irrigation (Chanjuan et al., 2021). More than half the species that originally lived in the Aral Sea have gone extinct since 1990 (Micklin, 2007). Similarly, overexploitation of the Ogallala Aquifer for agricultural use in North America, has led to an ongoing decline in water levels and quality, leading to the drying of unique arid land springs and streams and the disappearance of their permanent inhabitants, and declines of migratory visitors (Dennehy et al., 2002). This overuse of aquafers is hugely significant, as many can take centuries to recharge, and the depletion of water can cause irreversible damage to ecosystems, species and economies which rely on water from these systems; yet the access to some is even being subsidised in some countries (Wada et al., 2010; Aeschbach-Hertig and Gleeson, 2012). Similarly, saline lakes around the world, including the Dead-Sea in Israel, are in decline. Many species in danger, especially migratory birds adapted to use these sites for critical parts of their annual cycle. The mismanagement of these systems will likely lead to the further collapse of saline lakes across Arid regions and the species dependent upon them for survival (Wurtsbaugh et al., 2017; Edwards and Null, 2019; Foroumandi et al., 2022). Saline lakes occur in many arid lands round the world (and are largely restricted to arid and semi-arid systems), and are essential for various migratory bird species, but with the shrinkage of lakes, and changing chemical properties due to agriculture in proximal regions, these changes have directly contributed to declining populations of many of these species (Senner et al., 2018; Naik and Sharma, 2022).

Resource extraction

Unsustainable use of natural resources, such as the overexploitation of biological resources, has led to large decreases in many native populations, with some becoming endangered or extinct. For example, the population of the shrub *Haloxylon ammodendron*, a dominant species in most desert ecosystems in central Asia, has been reduced by 60% in the Junggar Desert in China and Mongolia due to droughts, and because of over-exploitation for firewood and livestock (Langming et al., 1998). Likewise, *Malus sieversii*, a dominant species of wild fruit tree in the Tianshan Mountains of Central Asia, has decreased in abundance by 50% as a consequence of human disturbance and changing climates (Si et al., 2011). Animals have also shown marked declines as a result of unsustainable use, for example the ongoing demand for ivory is driving an alarming decline in African elephant populations (Harris et al., 2019) The illegal trade of various animals and succulent plants from arid African countries has recently increased substantially (Margulies et al., 2019; Lavorgna et al., 2021), for example 1.5 million rare succulents, largely from the genus *Conophytum* were removed from a single protected area in South Africa alone, and with new infrastructure planned for the Succulent Karoo region where these species originate, international trade may be set to increase. Similarly, cactuses are fast declining in the arid regions of the Americas with 47% of species collected for the horticultural trade and third of species threatened with extinction (86% of species threatened by trade come from the wild) and the conversion of agricultural land (Goettsch et al., 2015). The same is true for various vertebrate taxa, for example arid ecosystems are hotspots of endemic reptiles in Madagascar, which are now threatened by a combination of over-collection for pet trade and habitat degradation (Jenkins et al., 2014).

At smaller scales such as the cold arid Himalayan regions at least 11 plants are prized by Hakeems (indigenous physicians) of Kashmir in India, and by Amchi medicine (Tibetan traditional medicine) practitioners, and illegal trade in these plants has persisted even after trade bans (Mushtaq et al., 2016). Likewise, Oleo gum trees (Guggulu in Hindi) are illegally overexploited for medicinal uses (Dhyani and Anurag, 2015), highlighting the need for better regulation even at local levels and small scales. Many species adapted for arid landscapes have slow growth to maintain water, and show high degrees of endemism (Klopper et al., 2020), thus hunting and collection of items in arid lands, without clear measures to ensure harvest is sustainable; can lead to rapid population declines. High endemism and small ranges in arid-ecosystem dependant systems is well known, thus loss and degradation of these regions as well as over-harvesting may have a disproportionate impact (McDonald et al., 2021), especially given that a diverse range of desert species have been restricted to small regions since even drier Holocene conditions and may be very range limited (Soultan et al., 2020), and deserts such as the Namib desert lay have been arid since the Cenozoic (33.9ma; Lancaster 1984). They may be particularly vulnerable to population declines, with slow rates of recovery. These ancient landscapes may also be particularly climate sensitive, for example the steppe-desert of Central Asia has existed since the Eocene, and analysis shows that the unique flora may not be able to adapt to new climate regimes (Barbolini et al., 2020). Furthermore, patterns of radiation and evolution in these arid ecosystems have occurred at different time periods, with cold arid periods during glacial maxima spurring diversification in areas such as the steppes of central Asia, and these little protected areas now represent important hotspots for the conservation of certain plant and animal taxa (Lioubimtseva, 2004). These types of ancient origins are common in many arid-land ecosystems, the Atacama provides another example, where isolation and diversification of various plant clades has occurred since the Miocene (Bohnert et al., 2022).

Global climate change and extreme weather

Changes in climate has already driven declines in the populations of valuable species, and the extinction or loss of range of some species in arid land, such as *Saiga tatarica* in the Eurasian steppes (Kock et al., 2018). Recent analysis shows that arid lands may be subject to various thresholded “tipping points” especially with regards to climate, and precipitation and temperature sensitivity may be far higher than previously realised (Berdugo et al., 2022). Consequently climate changes has caused floristic reorganization and from an increase in precipitation in Arizona, North America (Borwn et al., 1997), as well as changes in floristic communities as a consequence of drought (Jürgens et al., 2018). Changes in climate (longer droughts and higher temperatures) can also impact on the biological soil crust (biocrust) (Reed et al., 2019; Rodríguez-Caballero et al., 2022) (especially in grazed areas), also undermining the capability of these systems to recover, and overlooking the unique biology of these regions. Furthermore, changes in climate have also been shown to change phenology and delay flowering in some regions, which may drive asynchronies and the potential loss of available pollinators (Daru et al., 2018). Arid and semi-arid systems may change in a variety of ways because of a changing climate, including changing phenology, structure and productivity (Wei et al., 2021), but analysis shows that given that these areas often have little elevational gradient, species adapted to deserts may be among some of the most vulnerable to climatic change (Vale and Brito, 2015; Lian et al., 2021).

Special consideration should be given to the impact of a further increase in aridity in current arid lands (as they may already be water limited) on soil fertility and nutrient stoichiometry; mainly at the level of the plant-soil nutrients cycle (Peñuelas et al., 2021). Field manipulation studies, where water availability decreased, have observed significant impacts in nitrogen (N) and phosphorus (P) changes in the plant-soil system (Jiao et al., 2016; Luo et al., 2018b). Increases in plant foliar N:P ratios in response to experimental drought are generally observed because low soil-water contents limit P uptake more than N uptake (Sardans and Peñuelas, 2013; He et al., 2014; Sardans et al., 2017a; Sardans et al., 2017b; Luo et al., 2018b). Biogeochemical cycles and nutrient stoichiometry have very significant implications on community composition, and the survival of desert endemic species (Griffis-Kyle et al., 2018; Sardans et al., 2021), highlighting the importance of soil research for conservation of arid systems.

Fragmented habitats

For species to remain viable, and to enable species to track climate by migrating with changing environments, requires renewed efforts to improve large-scale connectivity of ecosystems, including arid lands. For example, a consequence of fencing and other forms of fragmentation (leading to longer routes, late arrivals, higher stress and higher mortality) is decreasing populations of migratory species such as Saiga in Asia, and elephants in large parts of Africa, a arid eco-systems may have disproportionately large proportions of large-bodied mammals that need to migrate following annual rainfall (Khanyari et al., 2022). Habitat fragmentation and the loss of key habitats from large-scale construction, mining, energy development, agriculture, and urbanization have led to a sharp decline in the populations of flagship species or the disappearance of some important species. For example, Caspian tigers (*Panthera tigris tigris*), whose range once spanned a vast area across Xinjiang in China and central Asia, went extinct in the 1980s due to intense human interference, including deforestation, development, and hunting (Chestin et al., 2017).

Invasions by alien species

Arid systems are particularly vulnerable to invasive species, especially after fire (Smith et al., 2000; Underwood et al., 2009). Invasion by alien species have driven ecosystem changes, population declines, the loss of biodiversity, and economic impacts. For example, the arid land in north-western China has 165 documented invasive species, 88 and 57 of which are plant and animal species, respectively, posing a grave threat to local ecosystems and biodiversity. The economic losses incurred from biological invasions in Xinjiang alone are as high as 1.249 billion Yuan (almost US$ 200 million) a year (Guo et al., 2017). In arid Africa, the spread of cacti and various North American succulents has become a problem and is increasingly leading to large-scale control efforts (Githae, 2018). Furthermore, initiatives to combat climate, such as the great green wall in Africa, can facilitate the invasion of non-native species, due to a weak legislation leading to the use of non-native species, often driven by economic rather than by ecological motivations (Jalam et al., 2021). These impacts are driven by the ongoing refusal of policymakers to address known risks associated with invasive species, such as outcompeting native species or modifying habitat structure (Perry et al., 2020) and by high propagule pressure due to the frequent use of non-native species in activities of development and management in arid regions.

Approaching these threats

Solutions to unsustainable Agriculture in Arid lands

Regarding agricultural and forestry related issues, the development of standards for exported goods which incorporate the environmental impacts of products would help reduce the market for unsustainably produced commodities. Engagement of the auto-industry which principally imports leather from Latin American arid lands is critical. The use of supply-chain tracking technologies and sustainability mandates can ensure that they are no longer responsible for the clearance of further natural areas, much of which is already illegal, to support cattle ranching (Earthsight, 2020). Such measures would be complemented by the tighter application of FSC (Forestry Stewardship Council) standards for exports of wood and charcoal products, which represent major threats to regions like the Gran Chaco. Some producers have been shown to have obtained FSC certification for export despite clear violations of standards (Dummet et al., 2021) and significant levels of illegal production (de Koning, 2020). However, such measures would not help minimize domestic and regional trade, as they only apply to international trade. Thus, in these regions in particular, renewed efforts to protect a larger and more representative dry land area are needed. Even small increases in protected area coverage could vastly expand the protection of sensitive species in these ecosystems (Goettsch et al., 2019).

Furthermore, policies around irrigation and water-use may help prevent the collapse of further ecosystems of the kind observed with the Aral Sea. To do this well requires multifaceted action, including better monitoring (using a range of approaches) of global groundwater reserves, the clear use of data to inform what can be sustainably extracted, and avoidance of the use of non-renewable groundwater (Mays, 2013; Bierkens and Wada, 2019; Hu et al., 2019). The depletion of groundwater is most acute in arid and semi-arid areas, and is only expected to get worse under a warming climate (Famiglietti, 2017; Dalin et al., 2017; Jsechko and Perrone, 2021). Furthermore, the high levels of endemism in desert springs associated with these systems highlights the need for identification of key sites of high endemism, and monitoring of flows, and other measures to ensure that groundwater depletion does not stop flow or alter the chemical composition (Fensham et a., 2011; Parker et al., 2021).

Conservation and sustainable use in arid lands can be particularly challenging due to the limited resources, as evidenced by camels. The last native Bactrian camel populations (*Camelus ferus)* in Mongolia are declining and critically endangered, in part from hybridization with domestic Bactrian camels (*Camelus bactrianus*) which are grazed proximate to the last wild herds. Conversely feral dromedary camels in Australia (*Camelus dromedarius*) now have an estimated population of over 1,500,000, which disrupt native habitat and require culling to just keep populations under-control (Burger et al., 2019). This highlights the sensitivity of arid lands, and the species dependent upon them, and the necessary sensitivity about introducing species (especially grazers) into these environments, and the need for careful management when bringing ungulates to areas with close relatives. Furthermore, whilst these ecosystems are often adapted for grazers, the impact of native grazing species are different from those of livestock, and prolongued grazing can damage arid ecosystems even when it does not require the clearance of original vegetation (McManus et al., 2018).

Solutions for unsustainable resource extraction

Regarding resource extraction, better measures are needed in the countries which import succulents, with many specimens travelling to, or via China and South Korea these transit points may also need to take action to prevent their role as end market drivers or conduits of an unsustainable trade. Additionally, education of buyers to enable them to select locally propagated plants, and regulations to help ensure this are needed, as many buyers are likely unaware that they have been importing unsustainable and often illegal sourced material (Margulies et al., 2019). In addition, initiatives such as FloraGuard that screens digital platforms for evidence of wild collected illegal material (Lavorgna et al., 2020; Lavorgna and Sajeva, 2021), need to be expanded. Ongoing addition of species, newly in demand from the ornamental horticultural trade onto the CITES appendices is also necessary.

Reducing the impacts of climate change on arid land

Working to identify vulnerable regions to climate change and exclude these regions from agriculture or development is needed, as recovery may be particularly slow, and once critical thresholds are crossed, and reductions in productivity can persist (Lohmann et al., 2012; Berdugo et al., 2022). Reducing the impact of climate change in these systems requires several actions. Firstly, the preservation of areas likely to show topographic buffering and thus act as possible refugia. Secondly, policies and regulations to prevent perturbing the water table are required to prevent further areas trying out with possible irreversible consequences for climate and communities (Micklin 2007).

Preventing impacts from fragmenting habitats

For migratory species in arid lands following annual rainfall patterns is likely to be essential to their continued survival. That fragmentation may be caused by both loss of habitat (fires, land conversion, agriculture), or the erection of barriers along parts of the route (Hughes 2019; Esler et al., 2017). Mitigating the impacts of infrastructure that can fragment these ranges requires ensuring these areas remain permeable, either by strategically placing fences where they do not intersect ranges, or by providing subways and overpasses for species to circumnavigate routes (Hughes 2019). The convention on migratory species (CMS) has similarly dedicated substantial effort to removing fences across many parts of central Asia, which created barriers to the migration of many species following seasonal rains (UNEP/CMC 2019). Efforts to maintain ecosystem connectivity and remove barriers across species migratory ranges are needed more widely (UNEP/CMC 2019), and active planning is needed to prevent ecosystems becoming fragmented. Actions to remove fences often stem from collaborative work between NGOs and local communities and governments, and has often been under guidance from the Convention of Migratory species.

Reducing risks from invasive species

Heightened efforts are needed to prevent the introduction of possibly invasive plant species into these fragile ecosystems and the ongoing spread of species previously introduced. Some arid ecosystems can be particularly vulnerable, with agriculture and tree plantations often causing the spread of invasive species into arid lands (Arasumani et al., 2018; Zaloumis & Bond., 2016). Reducing the risk of invasive species requires better valuing arid lands and not using these landscapes as plantations (Parr et al., 2014; Veldman et al., 2015), especially with non-native species which may colonise arid lands, and may also alter the watertable, and recognition of "old-growth arid lands" may facilitate prioritisation for these landscapes (Veldman 2015b).

Overarching solutions and how to make them successful

Although all these mechanisms behind species and ecosystem decline and degradation are global, their impacts are often especially felt in developing countries which have higher rates of population growth, poverty, and land-use change. Furthermore, challenges with corruption and poor governance may also play a role in failing to adequately conserve biodiversity. Strategic plans must better acknowledge that sustainable development requires a baseline against which to measure sustainability, and thus to enable the systematic protection of arid lands and the species dependent upon them. Solutions to these challenges rely both on the region and the drivers of the issues. A lack of adequate policies and poor management and regulation has generally led to a lack of a systemic approach to protecting habitats and species (Fig. 2), many arid land ecosystems are degraded and are rarely prioritised, or restored in an appropriate way (Dudley et al., 2020). Research database coverage and information-sharing on biodiversity in arid lands are shockingly inadequate (Bonkoungou, 2001), inhibiting the development of appropriate approaches to conservation and management. The main challenges in implementing the UN's Convention on Biological Diversity in arid lands is multifaceted, including species biology and social, economic, and political arenas within which people operate. Effective conservation must transcend the theoretical to provide practical and site-appropriate recommendations for conservation and management. Furthermore, efforts to combat climate change through planting trees in deserts and savannah lands are at fundamental odds with ecology and biodiversity, potentially facilitate the spread of invasive species (Brundu et al., 2020), and may drive major biodiversity loss, whilst failing to deliver on climate targets (Bond et al., 2019; Naia et al., 2021). More ecologically appropriate nature-based solutions are needed, ones that acknowledge the synergies between biodiversity and climate targets, rather than naïve approaches which fundamentally undermine our ability to conserve ecologically fragile areas (Seddon et al., 2021) and frequently see low rates of success (Ahrends et al, 2017), whilst also overlooking the potential of these landscapes to effectively store carbon without human interventions (Hanan et al., 2022). In arid lands, normally with nutritional poor soils, plant invasion success is associated with more conservative use of N and P and retention capacity (Sardans and Peñuelas, 2013). Thus, alien plant occupation of soil space modifies soil condition in a way that makes colonization of native species especially difficult. This makes arid lands very vulnerable to plant invasion in terms of potential loss of native species biodiversity.

Efforts and strategies for conserving biodiversity in arid lands

Developing countries in central Asia and Africa are the archetypal representatives of global arid lands, but far from the only examples. Although strategies to conserve biodiversity at national and international levels have been practiced, these efforts have received much less attention than necessary, and protected area coverage is still low (Fig. 2). For example, large protected areas in Pamir-Alay, Tajikistan, have been established in recent decades, including 22% of the country's territory, but few are devoted to floristic conservation compared to faunal conservation (Nowak et al., 2020). Five central Asian countries, i.e., Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, currently have 286 protected areas, accounting for 8% of their total terrestrial area - far lower than in most developed countries (Blank and Yang, 2013; CAREC, 2015; CBD, 2013, 2018). Several of these countries have established Red-Data Books for species at the regional level, but they remain incomplete, and even when threats are known, often the appropriate solutions are not enacted. The underlying problems for effective species and ecosystem conservation, are known, and solutions have been available for decades (Dregne, 1986), but many programs are ineffective, and effective programs for monitoring and managing arid lands are still only targeted at a small number of regions (Briggs et al., 2019; Silcock and Fensham, 2019).

We cannot afford to overlook the importance of arid lands to indigenous communities across the planet (Avaaz 2022). Thus, decision making on the management of these environments at all levels also requires the inclusion of indigenous communities who are often reliant on these landscapes and suffer disproportionately from their degradation. The needs of these communities cannot be neglected in securing the long-term future of these regions, thus inclusion through decision-making processes, education, recognition and valuation of ecosystem services (Kellner et al., 2018), and programs for poverty alleviation are needed given the high populations occupying these regions (Gannon et al., 2020). Developing better means to assess carrying capacity and harnessing new technologies to enable the sustainable use of arid lands for those dependent upon them is critical. In the future, arid lands will need to sustain bigger populations, and better approaches will be required to balance the conservation of natural biodiversity with human pressures.

The way forward to conserve biodiversity

For the post-2020 framework to be inclusive and effective, direct goals and recommendations are needed (Zhu et al., 2021). The recent Glasgow declaration on forests and land use (https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/) featured similar themes, but we have failed to convince the world of the crucial importance of biodiversity in general and in arid lands in particular. Continuing challenges in implementing biodiversity loss control programs require clear institutional mandates. Clearly identifying the roles and responsibilities of different institutions in the process of biodiversity conservation is essential, as it helps to enhance accountability and transparency. Many of the solutions or strategies for biodiversity conservation in arid lands in the proposed framework directly come under the jurisdiction of inter-governmental commitments, and collaboration is needed for these to be genuinely effective (Hughes et al., 2022). Fund mobilisation and legislation obviously needs the national government to enable the strategic mandates for the local government and communities to manage, conserve, and sustainably use biodiversity and ecosystem services, and the transfer of technology and building of capacity may be needed to reach these aims. However, many components of the proposed framework are multi-scaled involving national, regional, and international agencies, such as representative protection of species and regions and preventing the unsustainable collection of arid land products. Applying these initiatives to all levels to conserve biodiversity globally and support the achievement of the Global Biodiversity Framework (GBF) is urgently needed.

Future action plans and research should consider the following measures and guidelines to achieve the goals described in the post-2020 global biodiversity framework of the Convention on Biological Diversity (CBD) (Fig. 3). The following recommendations could be applied to best protect the unique diversity of arid land systems:

1. Resources extracted from arid lands should be extracted below the system's maximum capacity, and local communities should assist (where necessary) in understanding maximum sustainable yield to enable sustainable harvests in arid systems. Systems of regulation and monitoring are needed (see Orr et al., 2022).
2. Renewed efforts for the more representative protection of arid lands are needed to enable the representative inclusion of arid ecosystems into global protected area efforts and to ensure enhanced connectivity in the face of climate change.
3. Irrigation systems must not have far-reaching effects on the water table, and species likely to impact water availability should not be planted within arid lands. Groundwater monitoring and management are needed to prevent irreversible declines in groundwater reserves and aquifers.
4. Grazing, must also account for impact and the herd-size and duration. The location of grazing sites must follow ecological principles to prevent irreversible damage, and ungulates in particular should not be grazed proximately to native herbivores where they may spread pathogens, disease, or even hybridise with wild species.
5. Supply-chains should be tracked for products derived from arid lands, including all major commodities. Engagement with major industries (such as the auto-industry for leather) should also be consolidated to create the mechanisms to prevent unsustainable of arid lands to agricultural systems.
6. Certification systems should be enhanced and used with tracking technology to ensure that products and commodities grown for export are genuinely sustainable and legal.
7. The illegal and unsustainable extraction of succulents from arid systems requires urgent attention. Methods to tackle export, import, access (including digital platforms), more rigorous checks at

borders (many are easy to conceal) and demand reduction approaches are needed, and recommendations such as those by FloraGuard should receive the necessary funding and support to enact.

8. Efforts also need to reduce physical barriers (such as fences) and reconnect degraded habitat patches are required. This includes the removal of existing barriers and special measures to reduce the resistance these barriers present with the development of new infrastructure and efforts to restore connections between fragmented habitat patches.
9. Urban development and arid land agriculture must avoid the use of potentially invasive species and must cease to regard arid ecosystems as “an empty space to plant trees”. The introduction of any new species (plant or animal) should be made based on clear ecological surveys to establish a baseline and ensure that efforts to restore arid systems have a clear environmental basis, and impact assessments should be mandated for the development of all native ecosystems.
10. The arid lands biodiversity data initiative should be developed to provide the guidance needed to map species distributions, monitor population changes, and enable evidence-driven management and policy development.
11. Capacity building of local communities in arid lands is essential regarding controlled grazing, preventing planting non-native plantations, maintaining groundwater levels, and sustainable management of vulnerable species in arid lands.

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Competing interests

The authors declare no competing interests.

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