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Nature's contribution to people in drylands

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Abstract

Humans depend heavily on nature. Drylands are home to 2.5 billion people, but the extent to which nature contributes to people (NCP) in drylands has been little explored. We examined the global contribution of nature to people, aiming to compare drylands and non-drylands. We predicted a lower contribution in drylands than non-drylands, largely because of the sparser population densities (peoples' needs) and more degraded status of natural resources (lower potential contribution). Consistent with expectation, nature's contribution was about 30% lower in drylands, with significantly lower values for drylands in Asia, Oceania, Africa and South America, but no difference for Europe and North America. Differences were due mainly to lower contributions from material and regulating contributions, i.e., the regulation of air quality, climate, water quantity and flow, soil protection and the supply of woody material, and potentially, lower use by people in drylands. Predicted declines in rainfall and increasing temperature are likely to place increasing pressure on nature to contribute to human well-being in drylands. A better understanding of nature's contributions to people would improve our ability to allocate limited resources and achieve sustainable development in drylands.

Introduction

The physical, social, cultural, and spiritual well-being of humans is highly dependent on nature (Diaz et al., 2018; Hill et al., 2021). Nature encompasses not only organisms and their ecosystems, but also ecological and evolutionary processes on Earth, resulting in both positive and negative consequences for humans and their quality of life (IBPES, 2019). Nature's contribution to people (NCP) has been defined as 'all the contributions, both positive and negative, of living nature' (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality-of-life (Diaz et al., 2018). Nature's contributions can be organised broadly into three categories: material contributions (e.g., food and energy), non-material contributions (e.g., recreation, spiritual services and experiences), and regulating contributions (e.g., clean air and good water quality). Material and regulating contributions are similar to the elements captured in the ecosystem services paradigm, whereas non-material contributions include attributes that relate to the quality of life, belief systems, or nature-based experiences (Diaz et al., 2018; Hill et al., 2021).

Implicit in the NCP concept therefore is not only what nature can provide, but also what people need; social justice, spiritual beliefs and their links to the natural environment (Pascua et al., 2017), regardless of whether these needs are realised (Chaplin-Kramer et al., 2019). The magnitude of these contributions, therefore, would be expected to be greater where people have the strongest association with nature and the greatest needs (Chaplin-Kramer et al., 2019). Therefore, we would expect stronger contributions to human societies where people have a closer connection with nature or derive a living from the land. Such associations would be expected to be greater in drylands, where 90% of the human population has relatively low standards of living (Reynolds et al., 2007). Yet, previous global assessments (e.g., Liu et al., 2023) suggest that it is in arid and semi-arid environments and developing countries, mostly drylands, where ecosystem degradation fails to sustain the needs of people, i.e., areas with the greatest benefit gaps (*sensu* Hill et al., 2021) compared with wealthy, less marginalised communities.

Despite global assessments of NCP (Chaplin-Kramer et al., 2019), we have a relatively limited understanding of how nature contributes to the lives and welfare of people in drylands. Drylands are important because they account for almost 40% of the terrestrial land area, and are home to about 38% of the world's population (2.5 billion people; Huang et al., 2017). Moreover, large areas of drylands are devoted to primary production, particularly fodder production for livestock (Prăvălie, 2016). This makes them more vulnerable to environmental changes associated with increasing aridity (Huang et al., 2017) than other, more mesic environments (Berdugo et al., 2022). Many people in drylands are marginalised, often in areas of political conflict (Global Conflict Tracker, 2023), with low standards of living and sometimes poor nutrition (Prăvălie, 2016). Areas where overall contributions are low have been shown to be associated with transitional climates (Liu et al., 2023), reflecting ongoing degradation and declines in nature itself, through, for example, land clearing, desertification, and atmospheric pollution. This suit of physical and environmental conditions likely places drylands at a greater risk of famine and global tragedy. Exploring how nature can contribute to people in drylands is critical if we are to balance the competing needs of people and the natural environment, a more equitable human society, and work towards achieving sustainable development of drylands.

Here we report on a study where we used environmental, social and biological data as surrogates for 18 contributions that nature can make to people in drylands (Hill et al., 2021). These contributions comprise seven regulating, six material, and five non-material categories. Drylands are defined as areas where the ratio of evaporation to average annual precipitation exceeds 0.65 (MEA, 2005), including dry subhumid, semi-arid, arid and hyper-arid areas. Previous studies have focussed on nature's contributions at global scales (Chaplin-Kramer et al., 2019; Hill et al., 2021) or explored the service provision of drylands rather than associating provision and people's needs (Maestre et al., 2022). Traditional ecosystem service approaches have focussed only on regulating and provisioning contributions such as primary production, carbon, and food, but neglect the actual non-material needs of dryland people.

Our study links the provision of tangible goods and services with human needs, endeavouring to provide insights into the connection between potential contributions from nature and the capacity of people in drylands to use these contributions. We asked the following two questions: First, does the average contribution to people in drylands differ from that in non-drylands, and if so, what is the nature of the difference in these contributions? We posit that drylands would have a lower overall (average) contribution. Our rationale is that drylands are less densely populated, and their environmental resources are more degraded and susceptible to global changes than non-drylands (Hill et al., 2021). Second, have drylands exhibited greater temporal declines in contributions over the past decades (1992–2018) than non-drylands? We would expect the affirmative, given the generally greater declines in environmental quality in drylands than non-drylands over the past half century, though this could be masked by a larger population size and therefore greater human need over that period.

Methods

We used the datasets of Liu et al. (2023); see Supplementary Text S1), and the assessment is briefly described as follows. A general simplified flow chart illustrating the process of calculating nature's contribution to people using air quality regulation (NCP3) as an example is presented in Figure 1.

Spatial datasets

We reclassified the European Space Agency Climate Change Initiative-Land Cover (ESA CCI-LC) product (European Space Agency 2018), as the core data indicating the change of nature for NCP assessment. Complex ecosystem classifications reduce the accuracy of some NCP calculations, so ecosystem classes need to be consolidated and reclassified to harmonize different terminologies. Reclassification and consolidation can simplify different terminologies prior to analyses, such as combining multiple forests into a single forest class. This process simplifies the computational steps and permits a more rapid assessment of NCP. We used 20 spatial datasets to make the 18 NCP assessments. Most raster datasets had spatial resolutions finer than 10 km, providing sufficient pixels for

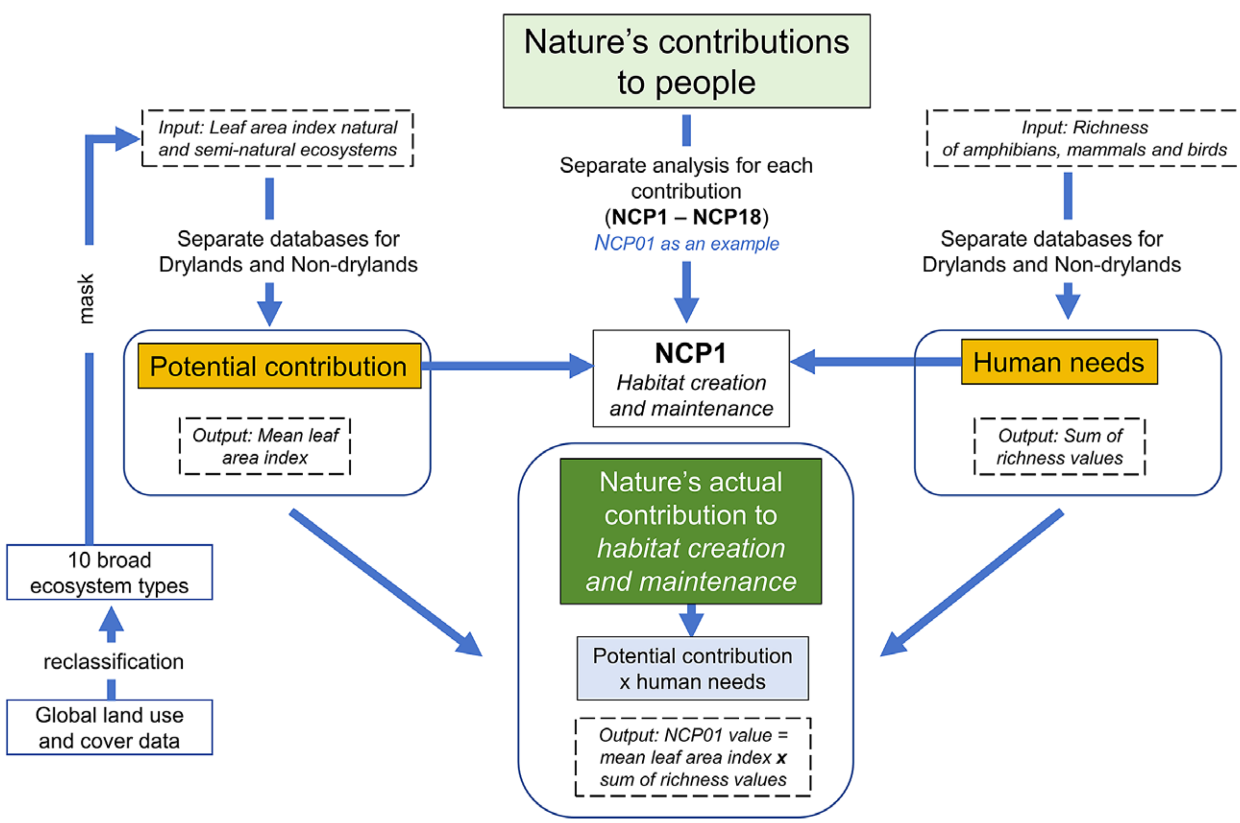

Figure 1 Air quality regulation (NCP3) as an example of a general simplified process for calculating nature's contribution to people.

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each sub-basin unit. Maps of the richness of mammals, birds and amphibians (Jenkins et al., 2013) at a resolution of 10 km were downloaded from BiodiversityMapping.org. The Global Inventory Modelling and Mapping Studies (GIMMS) provided the vegetation leaf area index (LAI)3g product at a spatial resolution of 1/12 arc degrees (Zhu et al., 2013). The global human settlement layer (GHSL) was downloaded from the Joint Research Centre (JRC) and included grids for built-up areas, populations, and settlements (Corbane et al., 2019). The gross primary production (GPP) dataset was estimated using a revised light use efficiency model, with a spatial resolution of 0.05 arc degrees (Zheng et al., 2020). The vectorized Global Mangrove Watch (GMW) datasets were transformed into 1 km spatial resolution data (Bunting et al., 2022) and evapotranspiration (ET) was a synthesized product with a 1 km spatial resolution (Elnashar et al., 2018). The MODIS (Terra Moderate Resolution Imaging Spectroradiometer Land Water Mask (MOD44W)) Version 6 data product was accessed from the Land Processes Distributed Active Archive Centre (LP DAAC) with a spatial resolution of 250 m (Carroll et al., 2017). Annual streamflow maps were obtained from the FLO1K dataset at a spatial resolution of 1 km (Barbarossa et al., 2018).

A pesticide risk score, based on the most popular active pesticide ingredient, was at a spatial resolution of 1/12 arc degrees (Tang et al., 2021). The soil erosion score was evaluated based on studies by Liu et al., (2019) at a spatial resolution of 1/12 arc degrees. The Harmonized World Soil Database was at a spatial resolution of 1 km (Fischer et al., 2008). Slope and elevation data were obtained from the Shuttle Radar Topography Mission digital elevation model at a resolution of 3 arc seconds (Jarvis et al., 2008). The aridity index (AI) was determined as the relationship between precipitation and evapotranspiration and mapped at a resolution of 30 arc seconds (Trabucco and Zomer, 2019). Floodplain data were at a 250 m resolution (Nardi et al., 2019). Data on the yield and aggregated value of crop production were derived from the Spatial Production Allocation Model dataset in 2010 (SPAM 2010) at a spatial resolution of 1/12 arc degrees (Yu et al., 2020). The "best crop" map that indicated the maximum achievable bioenergy yields was derived from the dataset of lignocellulosic bioenergy crops at a spatial resolution of 0.5 arc degrees (Li et al., 2020). Aboveground carbon biomass density data were derived from a 2010 harmonized map at a spatial resolution of 300 m (Spawn et al., 2020). Nighttime light data were obtained from a harmonized dataset from two satellites at a spatial resolution of 30 arc seconds (Li et al., 2020). The locations of natural and mixed world heritage sites were obtained from WHC.UNESCO.org. The vector road dataset was downloaded from the Socioeconomic Data and Applications Centre (SEDAC) and named Global Roads Open Access Data Set, Version 1 (gROADSv1; SEDAC 2013). We applied the HydroBasin level 06 in the HydroATLAS database to take advantage of the nested sub-basins at multiple scales for regionalization (Linke et al., 2019). To accommodate the spatial resolution of the various spatial datasets described above, the units smaller than 500 km^2 were merged into adjacent largest units to include more than four pixels of 1/12 arc degree raster data in a basin. This resulted in a database of 15204 basin units.

Spatial assessment

The assessment of NCPs uses an indicator-based approach with two indicators: 1) nature's potential contribution, and 2) nature's actual contribution to people (Table 1). Nature's potential contribution relates to the potential to provide resources, services, knowledge or inspiration. For example, nature contributes to the regulation of crop pests (NCP10) by supporting a diverse community of birds (Mayne et al., 2023). This contribution depends on whether a given basin unit supports crops that require this pest regulation or whether there are people who can benefit from this pest regulation. Although the potential contribution may be large, the actual contribution may be zero, due to an absence of people or crops, for example, the inability of people to use products derived from nature. Because actual human requirements from nature generally increase as population size increases, we set the population as static so that we could observe changes in NCPs driven by nature changes alone, i.e., in the absence of population increase. Put

Table 1. Description of nature's actual and potential contribution to people (adapted from Liu et al., 2023)

NCP	Description (after Diaz et al., 2018)	Contribution type	Potential contribution to people	Actual contribution to people	Weighted parameter	Data sources
NCP1: habitat	Habitat creation and maintenance	Regulating	Natural and mixed ecosystems: potential natural habitats	Actual animal biodiversity (mammals, birds and amphibians)	Animal biodiversity	Amphibian, mammal and bird richness BiodiversityMapping.org
NCP2: crop pollination	Pollination and dispersal of seeds and other propagules	Regulating	Mix ecosystems: key place of seed dispersal to cropland	Production for cross-pollinated crops: yield of crops required pollination	Production for cross-pollinated crops	Extent of natural vegetation within a 3 km buffer of cropland
NCP3: air quality regulation	Regulation of air quality	Regulating	Vegetation Leaf Area Index in natural and mix ecosystems: potential pollution entraining vegetation	Built-up land requiring pollution entrainment: actual emission from human habitat required entrainment	Built-up land and vegetation leaf area index	LAI data from Global Inventory Modeling and Mapping Studies (GIMMS)
NCP4: climate regulation	Regulation of climate	Regulating	Gross primary productivity in perennial vegetation: carbon sequestration	Default: not valued because of the global scale requirement	Gross primary productivity	Gross primary productivity (GPP) databases
NCP5: ocean acidification regulation	Regulation of ocean acidification	Regulating	Amount of mangrove forest on the coast: a key place of long-term carbon sink from ocean	Default: not valued because of the global scale requirement	Distribution of mangroves	Mangrove distribution data (1996 – 2016)

(*Continued*)

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Table 1. (*Continued*)

NCP	Description (after Diaz et al., 2018)	Contribution type	Potential contribution to people	Actual contribution to people	Weighted parameter	Data sources
NCP6: water quantity and flow regulation	Regulation of freshwater quantity location and timing	Regulating	Evapotranspiration in natural and mixed ecosystems: participation of ecosystem in water cycle	Streamflow: actual requirement for flow regulation by ecological processes including evapotranspiration	Evapotranspiration and streamflow	Terrestrial evapotranspiration data
NCP7: water quality regulation	Regulation of freshwater and coastal water quality	Regulating	Natural ecosystems surrounded rivers: natural capacity on decontamination	Nonpoint source pollution indicated by pesticide risk: actual requirement for decontamination	Water location and pesticide risk	Permanent water bodies within the MOD44B database
NCP8: soil protection	Formation protection and decontamination of soils and sediments	Regulating	Soil retention of natural ecosystems: the potential amount of soil retention	Soil fertility indicated by organic carbon: actual contribution of fertility retention	Soil retention amount and organic carbon	Harmonized World Soil Database in conjunction with Revised Universal Soil Loss Equation (RUSLE) modelling
NCP9: hazard regulation	Regulation of hazards and extreme events	Regulating	Natural ecosystems reduce landslide, desertification, flood and storm tides	Value of crop productions: agricultural value benefits from hazard prevention	Distribution of drylands and floodplains, slope, and crop production value	Combination of Global-Aridity_ET0 database, GFPLAIN 250 m dataset, and VP CROP A production database
NCP10: pest regulation	Regulation of detrimental organisms and biological processes	Regulating	Bird biodiversity in mix ecosystems: pest enemy diversity for agricultural production	Value of crop productions: actual value of crops prevented from pest	Bird biodiversity and crop production value	Aggregated value of production dataset
NCP11: bioenergy	Energy	Material	Shrub, grass and mix ecosystems: potential land for bioenergy plants in high probability	Potential lignocellulosic bioenergy crops: score of bioenergy production could be harvested	Lignocellulosic bioenergy crops	Lignocellulosic bioenergy crops dataset
NCP12: food	Food and feed	Material	Cultivated and mix ecosystems: potential land for food production	Yield of production for food crops: actual yield of food crops	Yield of food crops	Food crop yield data from the global synergy cropland layer in the SPAM dataset
NCP13: wood material	Materials, companionship and labour	Material	Forest ecosystems: potential land for logging	Aboveground biomass carbon density: actual yield of logging	Aboveground biomass carbon density	Aboveground carbon biomass datasets
NCP14: medicine	Medical, biochemical and genetic resources	Material	Diversity of natural and mix ecosystems: species diversity indicated by landscape diversity	Rural population: local people potentially using native herbal medicine	Natural landscape diversity and rural population	Shannon's landscape diversity index and global population databases
NCP15 learning and inspiration	Learning and inspiration	Non-material (cultural)	The diversity of ecosystem: diversity of nature, include artificial landscape	Social development indicated by nighttime light: people's requirement in a developing society	Landscape diversity and nighttime light	Shannon's landscape diversity index and nighttime light databases
NCP16: experience	Physical and psychological experiences	Non-material (cultural)	Density of natural and mix World Heritage sites: proximity of unique natural landscape	Accessibility indicated by road density: people's accessibility to get the unique experience	Density of natural and mixed world heritages and road density	World heritage database
NCP17: identity	Supporting identities	Non-material (cultural)	Change rate of landcover: landscape stability	Population on the changed landscape: actual amount of people within identity shaping	Rates of land cover and population changes	European Space Agency Climate Change Initiative Land Cover datasets
NCP18: options	Maintenance of options	Mixture of all three	Diversity of the other 17 NCPs	Diversity of nature to provide future benefits	Shannon's diversity index	Shannon's diversity index of NCPs 1 to 17

The data sources indicate the source of information used to assess both the potential and actual contribution to people, as well as the parameter (weighted parameter) used in the calculation of actual contribution.

simply, increases in human requirements could lead to an increased NCP assessment, which could mask any potential threats of natural ecosystem loss, and lead to perverse landscape management outcomes (Chaplin-Kramer et al., 2019).

The indicator framework was used to calculate a globally rapid assessment of all NCPs to identify spatiotemporal heterogeneity of the distribution rather than simulating a defined value for biophysical units. In order to develop a rapid assessment framework, no more than three global parameters were used for each NCP, except for hazard regulation (NCP9), which required four parameters to adequately parameterize. Details of the procedures and datasets used to calculate each NCP are given in Supplementary Text S1 and Figure 1. The lowest values of the parameters were assigned a value of 0, and the threshold value of 1 was set as the 90th percentile value of each originally assessed NCP value in 1992. All the values exceeding the threshold should be assigned as 1. By min-max normalization, the normalized value of every NCP was in the range of 0–1. Note that we did not change people's needs between 1992 and 2018 (see Supplementary Text S1).

Linear models (Bates et al., 2015) were used to examine differences in mean NCP values between drylands and non-drylands in relation to 1) six continents, 2) individual contributions, and 3) between 1992 and 2018. We tested for the correlation between the value of each NCP and population size using Pearson's *r*. Analytical tests were performed in the R statistical software (R Core Team, 2021) prior to linear modelling to ensure that the data met the necessary assumptions implicit in linear modelling.

Results

Nature generally contributes less to people in drylands

The global average value of NCP was about 30% lower in drylands than in non-drylands (χ^2 = 47.3, df = 1, 114, $P < 0.001$, Figure S1), consistent with our prediction. Nature's contributions to drylands were significantly lower for Africa, Asia, Oceania and South America, but there were no differences for Europe or North America (dryland/non-dryland by continent interaction: χ^2 = 15.2, df = 5, 114, P = 0.009; Figure 2). There was a small (albeit non-significant; $P > 0.21$) decline in NCP with increasing continent size for drylands, but not for non-drylands. We also found evidence of an increase in the magnitude of NCP with increasing population size, particularly for air quality regulation (NCP3), food (NCP12), medicine (NCP14) and learning/inspiration (NCP15; Table S1). Identity (NCP17) declined strongly in both drylands and non-drylands with increasing population size (Table S1).

We then focused on the average contribution to people across global drylands for different locations, i.e., the average value across all 18 contributions and considered both potential (Figure 3a) and actual (Figure 3b) contribution. We found extensive areas of low actual NCP in North Africa (Algeria, Libya, Niger, Mauritania, Mali, Chad, Egypt, northern Sudan, northern Ethiopia), West Africa (Namibia and South Africa), the west coast of South America (northern Chile and Patagonia), much of inland central Australia, the Arabian Peninsula, western Eurasia (Afghanistan, Iran, Turkmenistan), and west-central China and Russia. Conversely, high

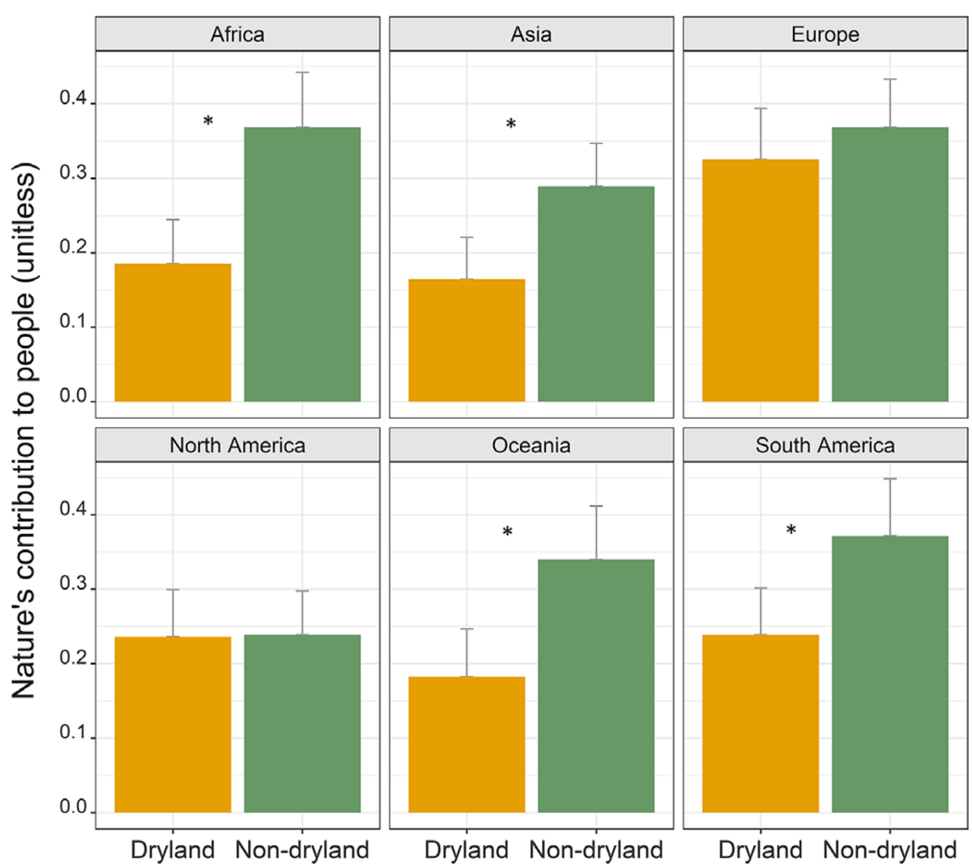

Figure 2 Nature's contribution to people (mean ± SE) for drylands and non-drylands by continent. Asterisks indicate a significant difference between dryland and non-dryland at P < 0.05. The number of dryland and non-dryland basins covered by each continent is as follows: Asia has 2,241 dryland basins and 2,774 non-dryland basins; Africa has 2,456 dryland basins and 888 non-dryland basins; Europe has 285 dryland basins and 924 non-dryland basins; North America has 677 dryland basins and 2,274 non-dryland basins; South America has 577 dryland basins and 1,204 non-dryland basins; and Oceania has 848 dryland basins and 56 non-dryland basins.

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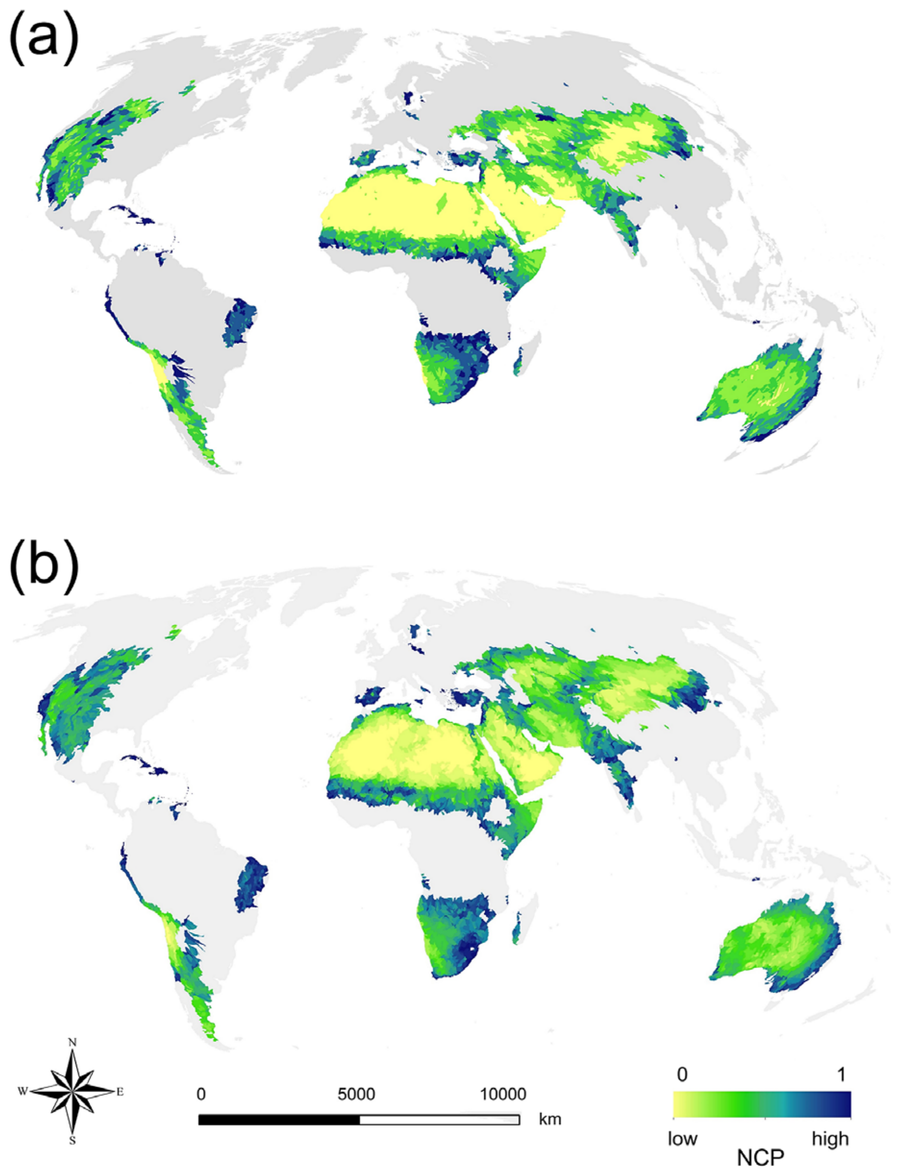

Figure 3 Mean (a) potential contribution and (b) actual contribution of nature to people in global drylands (average of 18 NCP categories).

values were more insular and occurred in southern India, north-eastern China, the Iberian Peninsula, western Turkey, south-eastern South Africa, north-western USA, and a narrow strip in north-eastern Brazil and coastal eastern Australia (Figures 3a and 3b). Although potential and actual contributions were spatially similar overall, actual contributions were greater for the Iberian Peninsula, the Indian subcontinent, and the eastern side of the Eurasian drylands (Figures 3a and 3b).

There were, however, large differences between drylands and non-drylands for specific contributions. For example, drylands contributed less to six of the 18 NCP categories, i.e., regulation of air quality (NCP3), climate (NCP4), water quantity and flow (NCP6), soil protection (NCP8; mainly in Asia and Oceania, Table S2), woody material (NCP13) and options (NCP18; Figure 4).

Spatiotemporal changes in nature's contributions

We found a general decline in NCP between 1992 and 2018 across all contributions and for both drylands and non-drylands ($-0.47 \pm 0.71\%$, mean ± SE) but this masked the changes in some contributions. For example, the average contribution by nature declined more in drylands than non-drylands for 10 contributions: habitat (NCP1), pollination (NCP2), oceans (NCP5), water quality (NCP7), soil protection (NCP8), hazard regulation (NCP9), pest regulation (NCP10) and bioenergy (NCP11), medicine (NCP14) and experience (NCP16), but increased for climate (NCP4), water quality/flow (NCP6), food (NCP12), woody material (NCP13) and options (NCP18; Table 2, Table S2), again consistent with our second prediction.

We also detected some spatial changes over the 26 years. The value of climate regulation in drylands increased in north-central and southern Africa, northern and south-western Australia, northern India, western Iran and western USA, but declined in central Australia and western China (Figures 5 and 6). For water quantity/flow regulation, we detected increases in north-central Africa, the Arabian Peninsula, northern Australia, much of mainland China, India and Iran, but declines were evident in northern and southern Africa, central, northern and eastern Australia, the Iberian Peninsula,

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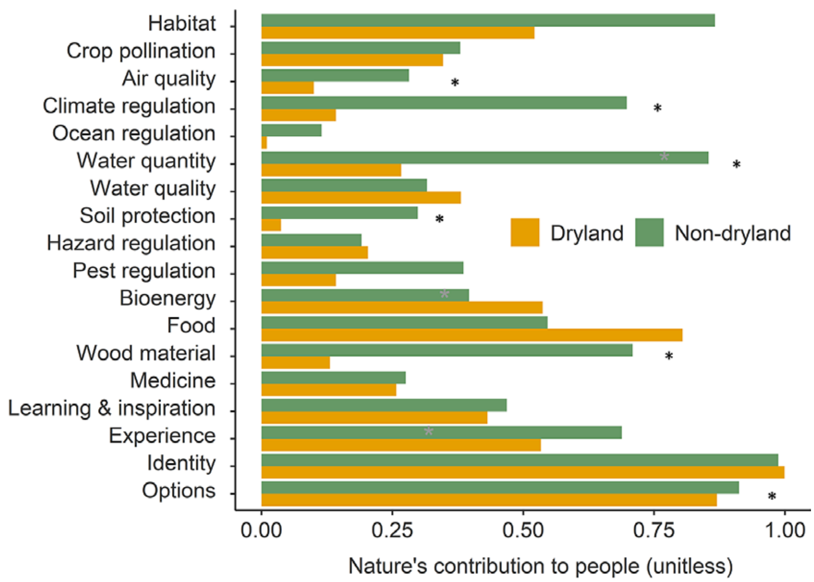

Figure 4 Mean contribution of each of the 18 NCP categories for drylands and non-drylands. Asterisks indicate a significant difference in contribution value between dryland and non-dryland at P < 0.05.

the western USA, and the west coast of South America. Similarly, there were some spatial declines in the value of pest regulation (NCP10) in drylands across extensive areas of Africa, the western USA and the western coast of South America, western Iran, northern India, central China, and large areas of Africa and central Australia.

Table 2. Percentage change in NCP for drylands and non-drylands between 1992 and 2018 and the dryland trend.

NCP code	Description	Dryland	Non-dryland	Dryland trend
NCP1	Habitat	–1.19	–0.89	Greater decline
NCP2	Crop pollination	–2.02	0.70	Greater decline
NCP3	Air quality regulation	–0.63	–0.73	Lower decline
NCP4	Climate regulation	11.11	1.10	Increase
NCP5	Ocean acidification regulation	–5.35	–4.32	Greater decline
NCP6	Water quantity and flow regulation	4.03	–0.20	Increase
NCP7	Water quality regulation	–1.86	–1.20	Greater decline
NCP8	Soil protection	–2.28	–1.01	Greater decline
NCP9	Hazard regulation	–2.62	–1.52	Greater decline
NCP10	Pest regulation	–5.43	–2.52	Greater decline
NCP11	Bioenergy	–0.48	1.53	Greater decline
NCP12	Food	2.95	2.31	Increase
NCP13	Wood material	1.11	–0.67	Increase
NCP14	Medicine	–1.47	–0.61	Greater decline
NCP15	Learning and inspiration	2.38	2.42	Lower increase
NCP16	Experience	–1.32	–0.77	Greater decline
NCP17	Identity	–3.32	–5.44	Lower decline
NCP18	Options	0.53	0.41	Increase

Discussion

We used an indicator framework to compare NCP in drylands with non-drylands. Unsurprisingly, the magnitude of this contribution was about 30% lower in drylands. These differences, however, were inconsistent across continents, with significantly lower values for drylands in Asia, Oceania, Africa and South America, but no difference in Europe and North America. Furthermore, we identified some hotspots of low contribution in North Africa, the Arabian Peninsula, central Australia, and west-central China, and high values in southern India, north-eastern China, the Iberian Peninsula, eastern Australia, and the north-west coast of the United States of America. Finally, potential and actual NCP values were similar, except for the heavily populated areas in Spain, India and China. Our results are consistent with the understanding that NCP is likely to be lower where the quality of the natural ecosystem or its capacity to produce is low (Chaplin-Kramer et al., 2019) and in sparsely populated drylands where the capacity of people to use nature's products is low (Brauman et al., 2020). Our results also suggest that the magnitude of nature's contribution globally will decline as drylands expand at the expense of non-drylands.

A spatial understanding of NCP in global drylands

Within those continents with a lower drylands contribution, we found that the reduction in contribution was due largely to a reduction in the magnitude of regulating contributions such as climate (NCP4), water quantity and flow (NCP6), soil protection (NCP8) and the production of woody material (NCP13; Figure 4), reflecting a generally stronger reliance upon primary resources by drylands in contrast to non-drylands (Brauman et al., 2020; Hill et al., 2021).

Three dryland areas characterised by low levels of regulating contributions and sparse population densities are North Africa (e.g., Algeria, Tunisia, Libya, and Egypt), the Arabian Peninsula, and central Australia (Figure 3). Low levels of climate regulation (NCP4) across these three areas result from the sparse forest and limited mid- and groundstorey cover (< 5% Maestre et al., 2021) dominated by short stature woody perennials and low stature herbaceous biomass (Fischer and Turner, 1978; Stafford Smith

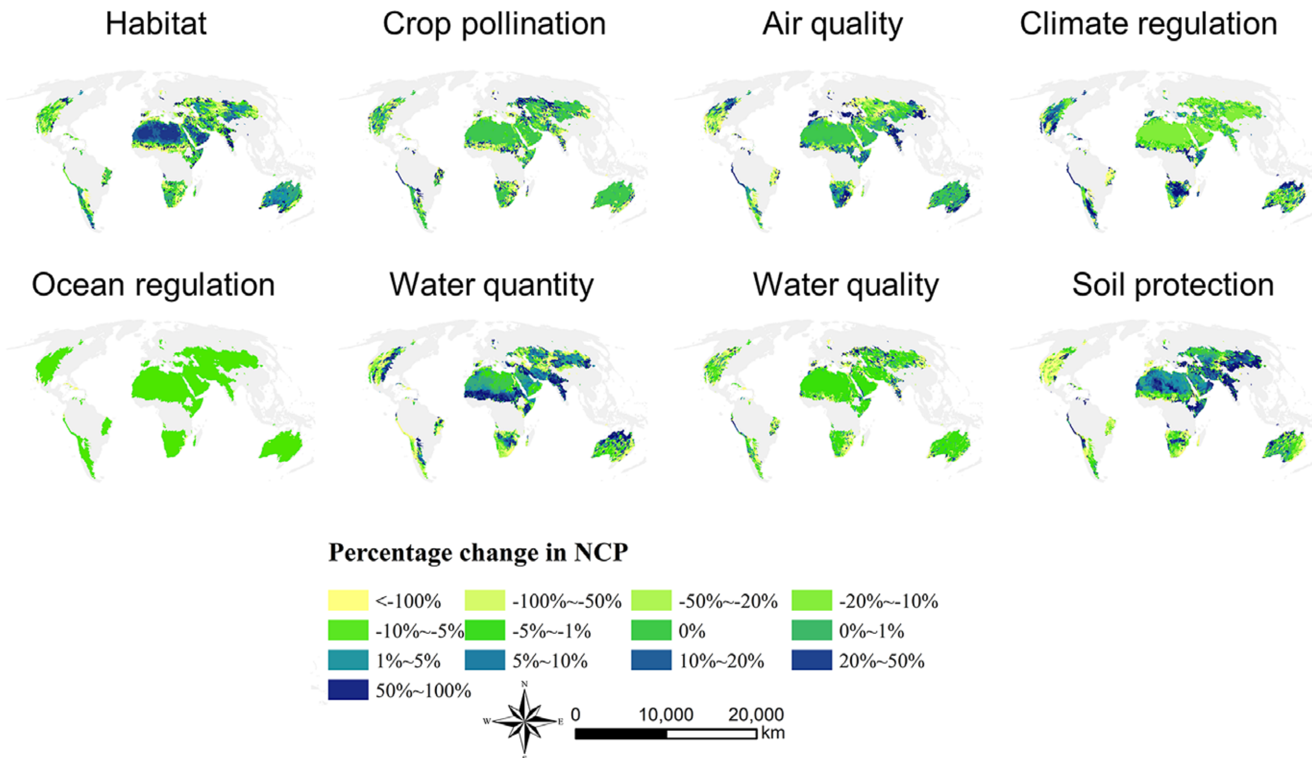

Figure 5 Spatiotemporal change in NCP1-NCP8 between 1992 and 2018 for drylands.

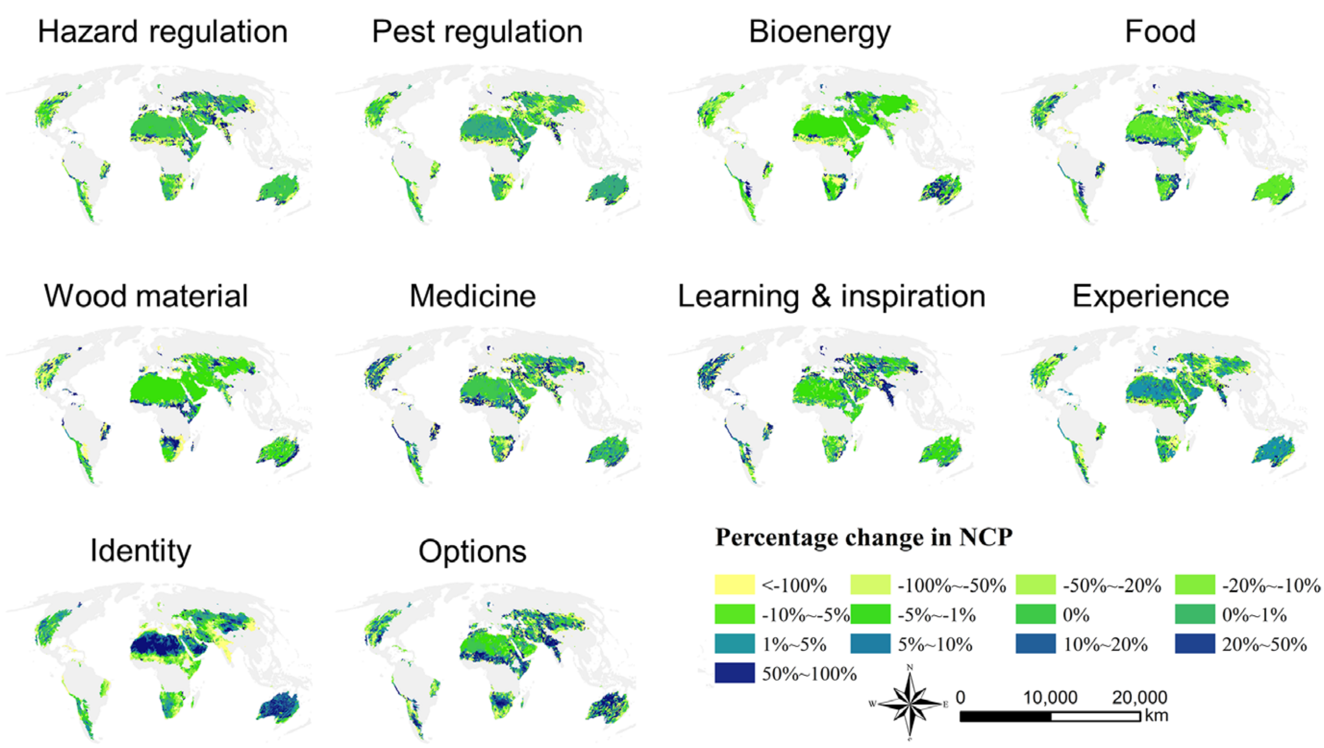

Figure 6 Spatiotemporal change in NCP9-NCP18 between 1992 and 2018 for drylands.

and Morton, 1999; Le Houerou, 2000; Brinkmann et al., 2011), but they often support a high plant species diversity (Maestre et al., 2021). Intense browsing and grazing by livestock, the dominant land use in drylands, reduces plant cover (e.g., Brinkmann et al., 2009), thus reducing the potential for capture of greenhouse gases and increasing climate-driven consequences for humans (Brauman et al., 2020). Vegetation cover and biomass are also critical parameters that influence the generation of aerosols, which are high over the Arabian Peninsula (Tandule et al., 2022) and North Africa (Gherboudj et al., 2017). It is unsurprising, therefore, that these three regions have a relatively lower capacity to support stable soils (NCP8) or extensive wood production (NCP13). The potential to produce wood suitable for sawmilling (NCP13) is also low due to the predominance of lower stature vegetation (shrublands at the expense of forests), highly variable precipitation, and high evapotranspiration (Stafford Smith and Morton, 1999). The only substantial difference in Europe was the lower value for woody material (NCP13) in drylands than non-drylands (Table S2), reflecting the dominance of short stature xerophytic shrubs with low potential for forestry in the drylands of southern Spain, southern Italy and west-central Poland. Importantly, yields of woody material are likely to decline due to the increased risk of droughts and wildfires in Europe exacerbated by changing climates (Górriz-Mifsud et al., 2022).

Large areas of North Africa remote from coastal influences are mapped as having low actual values of water quantity and flow regulation (NCP6, Figure 3b). Many North African countries face severe environmental challenges due to water scarcity (Hamed et al., 2018), which compromises agricultural industries that rely heavily on water supply (Radhouane, 2013). Surface and groundwater sources are sparsely distributed in North Africa and the Arabian Peninsula (Siebert et al., 2015), and surface water is scarce in central Australia, where it is held for only short periods in isolated depressions and ephemeral waterways (Brim Box et al., 2022). Consequently, most perennial vegetation is dependent entirely on groundwater (Eamus et al., 2006). Large areas of the Arabian Peninsula also lack surface water but have the capacity to access aquifers recharged from sporadic river flooding (UNDP/RBAS, 2013). Overall, these three examples of drylands are more sensitive to increasing dryness associated with climate change than non-drylands.

Implicit in the NCP concept is population size, and therefore potential contribution to people. We found generally positive relationships between NCP values and population size (Table S2), consistent with our understanding that population size and ecosystem production are positively correlated (Luch, 2007). Our three focal drylands are all relatively sparsely populated, with densities of 0.1, 1 and about 4 people km^{-2} for central Australia, the Arabian Peninsula and North Africa, respectively (Gapminder–Systems Globalis, 2022). Values of some NCPs (e.g., air quality, food production, medicine, pest regulation, and learning inspiration) were significantly related to population density in both drylands and non-drylands (Table S2). However, identity (NCP17) declined with increasing population size, possibly reflecting the alienation of traditional knowledge at large spatial scales or where populations are changing rapidly (Darvill and Lindo, 2015).

Average contribution values for drylands in two continents, Europe and North America were similar to values in non-drylands. North American and European (southern Spain, Sicily) drylands are densely populated, have relatively large GDPs, and highly mechanised primary production (Al Shamsi et al., 2018; Baur and Iles, 2023; Martínez-Valderrama et al., 2024). For example, the drylands in Almeria, on the Iberian Peninsula in Spain support a mixture of wooded Mediterranean forest and grassland located within a matrix of industrial agriculture such as greenhouses and irrigated agriculture (El Ghafraoui et al., 2023) and support a moderate population density of about 80 persons per km^{-2}. This is reflected in the high value of NCP12 (food) in drylands (Table S2). Extensive areas of farmland in Spain are located near Córdoba and Seville, the most developed locations since antiquity (Martinez-Valderrama et al., 2023), and this area is regarded as a food bowl for Europe (Ayuda and Pinilla, 2021). Furthermore, desert regions of Almeria are highly iconic and display unique landscape features ('badlands' Zgłobicki et al., 2021) that many city dwellers will not normally experience. People prefer these natural, albeit highly eroded, landscapes more than greenhouses. This likely reflects the high value that the population places on natural landscapes and landscape diversity, which should be reflected in learning and inspiration (NCP15) and identity (NCP16). North American drylands are also highly developed, support large urban centres, and include iconic desert environments with extensive natural and mixed ecosystems (NCP1) with potential for bioenergy production (NCP11; Nabhan et al., 2020), and areas that are accessible to people for experience of the natural world (NCP16, Table S2).

A greater decline in NCP in drylands

The magnitude of nature's contribution has declined markedly over the past half century (e.g., Brauman et al., 2020; Liu et al., 2023), and results between 1992 and 2018 indicate a substantially greater decline in drylands than in non-drylands (Table 2, Figures 5 & 6). Importantly, the greatest declines were for pollination (NCP2, 65% decline), soil protection (NCP8, 56%), hazard regulation (NCP9, 42%), pest regulation (NCP10, 54%), medicine (NCP14, 59%), and experience (NCP16, 42%). Potential contributions have declined for virtually all regulating contributions, e.g., plant pollination and pest regulation (Potts et al., 2016), and most declines have been due to a loss in environmental quality (e.g. Liu et al., 2023). Non-material declines are also evident, for example, with increased urbanisation removing local communities and indigenous people from their connections with the land and natural environments (Soga and Gaston, 2016).

Many of nature's contributions, particularly material contributions, are based on vegetation-related proxies. One might expect, therefore, a generally lower contribution in drylands than non-drylands, though this was not always the case (e.g., Figure 4). Improvements in database quality and the availability of more specialised data on different contributions at finer spatial scales in drylands should lead to a more reliable assessment of the relative differences between drylands and non-drylands, particularly if new proxies are more closely aligned to particular contributions. It is clear that the benefits accruing from nature are likely to be greatest where nature is most intact (Chaplin-Kramer et al., 2019), suggesting that areas suffering from environmental degradation will contribute less. The consequences of increasing aridity are that nature's contributions to drylands will continue to decline, particularly for dryland types that are most susceptible to changing climates. Distinct dryland sub-types are likely to respond differently to climate change (e.g., hyper-arid compared with dry subhumid) simply because nature's contribution depends on both the potential contribution (which is dependent on vegetation and therefore rainfall) and realised contribution (lower population sizes and therefore lower demand for material, non-material and cultural contributions). Thus, a more detailed assessment of different dryland subtypes would likely reveal how increasing global dryness might alter nature's contributions. Our results indicate that any declines in the environmental quality of drylands will have not only environmental implications but will impact human health (medicine) and the physical and psychological experiences that humans derive from nature.

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Conclusions

We used relatively predictable, intuitive, yet simple proxies to calculate NCP in drylands. We acknowledge, however, that our capacity to improve these estimates is hampered by the lack of available databases at the scale commensurate with drylands and non-drylands, and/or the lack of more nuanced information that is more closely aligned with a given contribution. This is particularly relevant for non-material contributions that relate to belief systems or personal experiences. Thus, our assessments can only be based on global databases and remotely sensed, broad-scale proxies. Advances in remote sensing technologies and access to databases at finer spatial scales should allow us to refine our assessment of nature's contribution in drylands, across large areas where data are sparsely distributed. Nonetheless, our study demonstrates that lower contributions to people in drylands can be attributed to the declining quality of environmental resources in natural systems (Liu et al., 2023; Table S1). The value of these attributes declines with declining rainfall and increasing dryness, yet their value (realised and potential) also increases with increasing population pressure. Predicted large-scale increases in aridity, combined with marked population increase and therefore accelerated land degradation (Prăvălie, 2016) are likely to place increasing pressure on nature to contribute to the physical well-being and function of drylands, its biota and people.

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Competing interest. The authors declare that they have no conflict of interest.

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