**Supplementary information**

**Nature’s contribution to people in Drylands**

David J Eldridge1, Chenxu Wang2, Yanxu Liu2, Jingyi Ding2, Yan Li2, Xutong Wu2 and Changjia Li2

1. Centre for Ecosystem Sciences, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, 2052, Australia
2. State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, China

**Supplementary Text S1. Description of the 18 NCPs, and databases and weights used**

**Indicator setting**

Most of the biophysical value of NCPs cannot be accurately spatially observed at the global scale. We construct 18 methods for assessing NCPs in this study for only rapid assessment. To give prominence to the contribution of the ecosystem itself as indicated by land cover changes between 1992 and 2018, the climatic fluctuation as well as the increasing demand from society have been static in the evaluation. Note that we did not change people’s needs between 1992 and 2018 for two reasons. First, if people’s current needs are greater than past needs, then nature’s contribution will be more valuable. People needs more from nature, so the strength of NCP will be greater, e.g., more pollution leads to a greater importance of vegetation surrounding urban areas and farmland. Conversely, if there is no pollution, air and water purification from nature is not needed. Second, there is a paucity of spatial data on people’s needs in the 1990s.

Based on the two indicator dimensions, namely, nature’s potential contribution from the prospective of nature’s potential provision and actual contribution to people from the perspective of actual human requirements, the indicator settings in these NCP estimations before the mean value calculated at the subbasin scale is listed as follows.

*Indicator in NCP1 (habitat creation and maintenance)*

We set the values of urban areas and croplands as 0 and natural systems as 1. The species richness of amphibians, birds and mammals is a commonly used indicator (Howard et al. 2020) of global biodiversity richness (Butchard et al. 2010). We used the following biodiversity maps: “Richness 10km AMPHIBIANS dec2017 EckertIV”, “Richness 10km Birds v7 EckertIV breeding no seabirds” and “Richness 10km MAMMALS mar2018 EckertIV”. These maps were summed after min-max normalization as a weight of importance for habitat creation and maintenance. This ecosystem classification value was multiplied by the biodiversity weight to form an assessment of NCP1.

*Indicator in NCP2 (pollination and dispersal of seeds and other propagules)*

Pollinators are under increasing threat from human activities and climate change (IPBES 2016). However, spatial pollinator datasets are generally unavailable, except for isolated areas (Dicks et al. 2021, Potts et al. 2016). A potential proxy of the contribution of pollinators to cropland is the extent of natural vegetation (mixed ecosystems, forest, shrubland, grassland) within a 3 km buffer of cropland (Schulp et al. 2014, O’Connor et al. 2021). Mixed cropland-natural systems can also support pollinators (Lasway et al. 2022), so along with natural ecosystems within 3 km of cropland were assigned a value of 1, and other systems a value of 0. We considered the production of cross-pollinated crops as a benefit to humans. We used the most up-to-date global synergy cropland layer in the SPAM dataset, and summed the yield layer of 21 cross-pollinated crops (Yu et al. 2020), which included maize, pearl millet, sorghum, sweet potato, yams, cassava, coconut, oil palm, sunflower, rapeseed, sugarcane, sugar beet, cotton, other fibre crops, Arabica and Robusta coffee, cocoa, tea, tobacco, temperate fruit, and tropical fruit. The ecosystem classification value was multiplied by yield weight to form the basic NCP2 assessment*.*

*Indicator in NCP3 (regulation of air quality)*

The value of urban ecosystem services is highly uncertain and is seldomly mapped (Keeler et al. 2019), particularly in drylands (Akhtar et al. 2022). Plant leaf area index (LAI) been been used as a proxy of the potential for removal of pollutants (Wang et al. 2014), so we used LAI of natural and mixed ecosystems as an indicator of potential regulation of air quality by nature. We averaged the continuous 5-year GIMMS LAI3g between 1988 and 1992 (“LAI 1992”), the GIMMS LAI3g between 2011 and 2015, because 2015 was the final year of this LAI product (“LAI 2018”). Values for urban ecosystems and croplands were assigned a value of 0 and others a value of 1, and then multiplied by the mean LAI values. For the actual contribution, we used the proportion of urban land as both the pollution pressure of human activity and human quality of life requirement. Thus, the value of air quality regulation would be higher for a larger area of developed land with a greater LAI. The proportion of built up land at the subbasin scale was multiplied by the mean values of LAI in natural and mixed ecosystems at the subbasin scale to form the basic assessment of NCP3.

*Indicator in NCP4 (regulation of climate)*

Gross primary productivity (GPP) is the largest carbon flux component within terrestrial ecosystems and plays an essential role in regulating the global carbon cycle (Zhao and Running 2010, Zheng et al. 2020). The GPP of annual plants is not a good indicator of carbon sequestration, so we used the GPP of woody plants (perennials) as a measure potential climate regulation, with potential climate regulation increasing with increasing woody plant production. As climate regulation provides a global benefit, we did not include a local requirement indicator in our calculations. However, a high-resolution greenhouse gas emission map could be used as the actual local requirement if the data exist. The values of forest and shrub ecosystems were set at 1, and others at 0. We averaged the continuous 5-year GPP for 1988-1992 (“GPP 1992”) and for 2013-2017 (“GPP 2018”) because 2017 was the final year of this GPP product. This ecosystem classification value was multiplied by the mean weighted GPP values to form the basic assessment of NCP4.

*Indicator in NCP5 (regulation of ocean acidification)*

Mangroves are forests that have high carbon stocks in the ocean carbon budget, and can potentially regulate ocean acidification (Worthington et al. 2020, Richards et al. 2020). We obtained global mangrove data (1996 to 2016) and summed the average subbasin level mangrove area in 1996 (“Mangrove 1996”) and the average subbasin level mangrove area in 2016 (“Mangrove 2016”). Similar to NCP4, we did not introduce a local indicator because ocean acidification regulation is a global benefit. However, a high-resolution coastal greenhouse gas emission map could be used as the actual local requirement if the data exist. Mangrove area at the subbasin scale was used to form the basic assessment of NCP5.

*Indicator in NCP6 (regulation of freshwater quantity, location and timing)*

Terrestrial evapotranspiration (ET) is a commonly used indicator of the water cycle. A greater ET indicates a greater potential contribution of the terrestrial ecosystem to the regulation of freshwater quantity, location and timing (Sterling et al. 2013). We averaged, continuous 5-year values of “synthesized ET” data for 1988-1992 (“ET 1992”) and 2014-2018 data (“ET 2018”). Urban and cropland areas were assigned a value of 0, and others a value of 1, and these were multiplied by the mean ET values. For actual contribution, a high ET in drylands should be avoided because it could reduce local streamflow and therefore freshwater supply for humans (Feng et al. 2016). We used the mean annual streamflow from FLO1K data (log10-transformed 1960–2015 data) to indicate the actual requirement for flow regulation by ecological processes, which include evapotranspiration. These values were multiplied to form the basic assessment of NCP6.

*Indicator in NCP7 (regulation of freshwater and coastal water quality)*

Riparian and coastal areas with natural vegetation provide effective nutrient retention and removal and therefore have the potential to sustain the quality of marine and fresh water (Mayer et al. 2007, Sweeney and Newbold 2014). We used a 3 km buffer around permanent water bodies in the 2000 to 2015 MOD44B database to mask the natural vegetated ecosystem classification. Values of mixed natural, forest, shrubland, grassland, wetland and water ecosystem classes were set as 1, and the others were set as 0. For actual contribution, we used the pesticide risk map (“global pesticide risk scores”) as a weight indicator. The greater the pressure from water pollution, such as from pesticides, the greater is the requirement for the regulation of freshwater therefore the greater the contribution to people (how much the people need). Consequently, the ecosystem value was multiplied by the pesticide risk to form the basic assessment of NCP7.

*Indicator in NCP8 (formation, protection and decontamination of soils and sediments)*

Prevention of soil erosion is a high priority in soil conservation (Wuepper et al. 2019). Conversion of natural systems to cropland can result in greater erosion (Sahu and Mohanty 2023). Although cropland has a degree of soil retention, it should not be regarded as of “nature’s contribution” because the function could be higher with natural vegetation. Thus, the values of the urban and cropland ecosystem classes were set at 0 and the others at 1. The Revised Universal Soil Loss Equation (RUSLE) was applied to the soil erosion estimation using existing data from Liu et al. (2018). The value of nature’s potential contribution was calculated as potential erosion without vegetation cover minus actual soil erosion (Fu et al. 2007). For actual contribution, our data were weighted by the value of topsoil organic carbon from the Harmonized World Soil Database. This because soil organic carbon is a good proxy of soil stability (Redmile-Gordon et al. 2020). Consequently, the soil retention value was multiplied by the soil organic carbon value to form the basic assessment of NCP8.

*Indicator in NCP9 (regulation of hazards and extreme events)*

For potential hazard regulation we selected three common hazards, including landslides, desertification, floods and storm tides, that are distributed in mountains, drylands, and humid and coastal areas. Slopes greater than 15o slope were deemed to require protection by native vegetation (Zhu et al. 2021). The values of mixed natural, forest and shrub ecosystem classes above the 15o slope were set at 1 and the others at 0. Using a dense tree cover to control land degradation in drylands is unfeasible due to low water storage in drylands (Ramon-Vallejo et al. 2002). Therefore, using values of the aridity index lower than 0.2 from the “Global-Aridity\_ET0” database, the values of mixed natural, grassland and shrubland ecosystem classes were set at 1, and the others set at 0.

Inland and coastal wetlands have the capacity to store and regulate floods and storm tides (Reis et al. 2017). Consequently, within the floodplain extent of the GFPLAIN 250 m resolution dataset, we fixed the mixed natural, forest, shrubland, wetland and water ecosystem classes at 1 and the others at 0. For the actual contribution, major food crops require hazard prevention. Accordingly, we used the aggregated value of the production of all crops as a weight (“spam2010V1r1 global V agg VP CROP A”). The unified set of the ecosystem class values was totalled as the proportion at the subbasin scale and multiplied by the aggregated value of production at the subbasin scale to form the basic assessment of NCP9.

*Indicator in NCP10 (regulation of detrimental organisms and biological processes)*

We are unaware of any global databases of detrimental organisms and biological processes. However, bird biodiversity could be potential effective proxy of detrimental organisms, as birds are upper-level predators in food webs (Letourneau et al. 2009). Moreover, major food crops provide an actual requirement for reducing detrimental organisms such as pests. Accordingly, we used the aggregated value of production mapped in NCP9 as the weight. The value of bird diversity in natural and mixed ecosystems was an existing assessment in the NCP1 calculation so multiplied the values of these two assessments to form the basic assessment of NCP10.

*Indicator in NCP11 (energy)*

In theory, all vegetation could be considered as planted bioenergy crops. However, here we considered the mixed cropland, mixed natural, shrubland, and grassland ecosystem classes to have a greater capacity for bioenergy exploitation than cropland and forest ecosystems. The values of these four ecosystem classes were set as 1, and the others were set as 0 in the calculation. Spatially explicit landscape-scale bioenergy data are rare (Dale et al. 2016). Typical bioenergy crops with a high carbon capture and storage are crop plants with high lignocellulose contents (Hanssen et al. 2020). We used the “best crop” data from the dataset yields of lignocellulosic bioenergy crops (Li et al. 2020) and multiplied the values of these two assessments to form the basic assessment of NCP11.

*Indicator in NCP12 (food and feed)*

For potential contribution, the values of the cropland and mixed cropland ecosystem classes were assigned as 1, and the others 0. For actual perspective, crop production data is available but not as raster data (Su et al. 2021). We summed the yields of 22 food crops from the latest global synergy cropland layer in the SPAM dataset (Yu et al. 2020). Livestock were not considered because they have the potential to be fed by crops.The data names were prefixed as “spam2010V1r1 global Y”. We multiplied the values of these two assessments to form the basic assessment of NCP12.

*Indicator in NCP13 (materials, companionship and labour)*

All ecosystems have the potential to provide materials, but the amount and requirement for companionship and labour are different. Forestry is a key indicator that supports both national development and local livelihoods (Elbakidze et al. 2013, Lund et al. 2018). In the potential perspective, we used the forest ecosystem as a sketch map for the absence of a global forestry raster map. The value of the forest ecosystem class was set at 1, and the others at 0. The shrubland ecosystem class was set as 0 as it is distributed mainly in dryland and unsuitable for extensive forestry. For actual contribution, the biomass of aboveground carbon was upscaled using the nearest neighbour method as a weight to indicate the yield of forestry. We multiplied the values of these two assessments to form the basic assessment of NCP13.

*Indicator in NCP14 (medicinal, biochemical and genetic resources)*

Natural products are importance sources of drugs (Newman and Cragg 2012). For potential contribution, all natural and mixed ecosystems were considered to have biochemical and genetic resources. Because there was no spatially explicit dataset for medicinal products from nature, we use Shannon's diversity index as a substitute, but excluded the urban and cropland ecosystem classes. For actual contribution, the rural population has a direct requirement for local natural medicinal resources. Rural location was extracted from the dataset “GHS SMOD POP2015 GLOBE R2016A 54009”, and multiplied by a population density dataset (“GHS POP E2015 GLOBE R2019A 54009”) to form the weight, and averaged at the subbasin scale. We multiplied the values of these two assessments at the subbasin scale to form the basic assessment of NCP14.

*Indicator in NCP15 (learning and inspiration)*

People are now less likely to have direct contact with natural environments and wildlife in their everyday lives (Soga and Gaston 2016). Assessments of the loss of local and indigenous knowledge from nature are mostly restricted to case studies with no spatially explicit databases (Eswani et al. 2018). For the potential perspective, we considered that learning and inspiration could depend on being exposed to a variety of different natural ecosystems. Therefore, we used Shannon's diversity index, a landscape diversity indicator, for all ecosystem classes. In the actual perspective, data on night-time light (1992 to 2018) were set as an indicator for the development of local society. Accordingly, more diverse ecosystems would be associated with greater societal development and a greater requirement for social learning and inspiration from the local landscape. The values of the diversity index and mean night-time light at the subbasin scale were multiplied to form the basic assessment of NCP15.

*Indicator in NCP16 (physical and psychological experiences)*

All ecosystems can provide physical and psychological experiences for humans, and here we focus on two essential indicators for uniqueness in the potential contribution and accessibility in the actual contribution. We used World Heritage ecosystems as our uniqueness value because of their high status in NCP governance due to their scarcity (Morrison et al. 2020). Accessibility indicated that the experience of nature could be realized by a visit (Balmford et al. 2014). The kernel density algorithm in ArcGIS was used, with default search radii, to interpolate the vector points of World Heritage sites and the vector lines of roads to raster maps, and the resolution was consistent with the ecosystem classification. The experience of the natural ecosystem was set at 1 and the urban and cropland ecosystem classes at 0 in our calculations. This ecosystem classification value was multiplied by the densities of World Heritage sites and roads as weights to form the basic assessment of NCP16.

*Indicator in NCP17 (supporting identities)*

Supporting identities provides a sense of place, are place-based, and often have spiritual significance for indigenous cultures (Pascua et al. 2017, Daniel et al. 2012). For potential contribution, all local landscapes have the capacity to support identities, including long-standing urban landscapes. Thus, landscape change could be considered a loss of capacity for supporting original identities. Based on our ecosystem classification, we used the European Space Agency Climate Change Initiative-land cover (ESA CCI-LC) change (1992 to 2005) dataset to enumerate the changing proportion at the subbasin scale (“1992”). We then used the land cover change in 2005-2018 period to enumerate the changing proportion at the subbasin scale (“2018”). Landscape change was set as 1, and areas of no change at 0. In the actual perspective, the gridded population on the changed landscape indicated the actual amount of local people with changing identity. The larger the number of people suffering from landscape change, the lower the value of supporting identities. Landscape change was multiplied by the number of populations to form the basic assessment of NCP17, and then a reverse normalization was processed.

*Indicator in NCP18 (maintenance of options)*

Previous studies have clarified the spatial distribution of vulnerable species, how humanity changes the planet, and how this drives extinctions (Pimm et al. 2014). Many land use projections indicate the future amount and pattern of landscapes (Stehfest et al. 2019). However, the maintenance of options includes so many aspects of nature that it cannot be simplified by biodiversity or landscape composition. According to the notion of a maintenance of options that do not belong to a single NCP category, all of the 17 NCPs need to be maintained into the future. There is no simple algorithm that could simultaneously anticipate the risk of loss of all 17 NCPs, we posit that diversity is positively related to the stability and diversity of the 17 contributions (Ives and Carpenter 2007). Consequently, the greater the diversity of NCPs, the greater the potential and actual ability of the overall contributions of nature to be maintained in the future. This was calculated as the Shannon's diversity index of 17 NCPs after normalisation, to form the basic assessment of NCP18.

**Table S1.** Pearson’s correlation coefficients (*r*) between population size and the value of each of the 18 contributions for drylands and non-drylands. ns = not significant.

|  |  |  |  |
| --- | --- | --- | --- |
| **NCP code** | **Description** | **Dryland** | **Non-dryland** |
| NCP1 | Habitat | -0.06 | -0.03 |
| NCP2 | Crop pollination | 0.07 | 0.12 |
| NCP3 | Air quality | 0.20 | 0.27 |
| NCP4 | Climate | -0.04 | -0.08 |
| NCP5 | Oceans | 0.14 | 0.06 |
| NCP6 | Water quantity/flow | 0.05 | 0.03 |
| NCP7 | Water quality | 0.07 | 0.13 |
| NCP8 | Soil protection | ns | 0.05 |
| NCP9 | Hazard regulation | 0.11 | 0.20 |
| NCP10 | Pest regulation | 0.13 | 0.22 |
| NCP11 | Bioenergy | -0.04 | ns |
| NCP12 | Food | 0.19 | 0.23 |
| NCP13 | Woody material | ns | -0.05 |
| NCP14 | Medicine | 0.41 | 0.46 |
| NCP15 | Learning inspiration | 0.33 | 0.32 |
| NCP16 | Experience | 0.09 | 0.19 |
| NCP17 | Identity | -0.57 | -0.61 |
| NCP18 | Options | 0.13 | 0.16 |

**Table S2.** Breakdown of magnitude of the contribution by NCP for drylands and non-drylands for the six continents

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| NCP code | North America | Europe | South America | Africa | Asia | Oceania |
| Dryland | Non-dryland | Dryland | Non-dryland | Dryland | Non-dryland | Dryland | Non-dryland | Dryland | Non-dryland | Dryland | Non-dryland |
| NCP01 | 0.43 | 0.33 | 0.18 | 0.29 | 0.52 | 0.87 | 0.42 | 0.83 | 0.24 | 0.41 | 0.39 | 0.48 |
| NCP02 | 0.10 | 0.08 | 0.35 | 0.38 | 0.28 | 0.34 | 0.11 | 0.29 | 0.11 | 0.21 | 0.08 | 0.12 |
| NCP03 | 0.03 | 0.09 | 0.10 | 0.28 | 0.02 | 0.05 | 0.01 | 0.04 | 0.01 | 0.08 | 0.01 | 0.09 |
| NCP04 | 0.14 | 0.28 | 0.05 | 0.14 | 0.13 | 0.56 | 0.10 | 0.57 | 0.01 | 0.24 | 0.14 | 0.70 |
| NCP05 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 | 0.00 | 0.02 | 0.01 | 0.11 |
| NCP06 | 0.17 | 0.47 | 0.22 | 0.44 | 0.27 | 0.85 | 0.15 | 0.77 | 0.12 | 0.54 | 0.10 | 0.60 |
| NCP07 | 0.19 | 0.27 | 0.38 | 0.32 | 0.14 | 0.26 | 0.04 | 0.16 | 0.09 | 0.22 | 0.03 | 0.27 |
| NCP08 | 0.03 | 0.06 | 0.04 | 0.06 | 0.01 | 0.06 | 0.01 | 0.09 | 0.01 | 0.11 | 0.01 | 0.30 |
| NCP09 | 0.08 | 0.05 | 0.20 | 0.12 | 0.06 | 0.11 | 0.08 | 0.19 | 0.06 | 0.13 | 0.04 | 0.04 |
| NCP10 | 0.07 | 0.07 | 0.14 | 0.11 | 0.14 | 0.25 | 0.14 | 0.39 | 0.09 | 0.21 | 0.05 | 0.08 |
| NCP11 | 0.47 | 0.11 | 0.20 | 0.21 | 0.48 | 0.40 | 0.39 | 0.32 | 0.12 | 0.13 | 0.54 | 0.35 |
| NCP12 | 0.17 | 0.10 | 0.80 | 0.55 | 0.18 | 0.21 | 0.10 | 0.20 | 0.21 | 0.26 | 0.08 | 0.09 |
| NCP13 | 0.11 | 0.36 | 0.13 | 0.43 | 0.09 | 0.57 | 0.04 | 0.49 | 0.01 | 0.40 | 0.07 | 0.71 |
| NCP14 | 0.03 | 0.06 | 0.26 | 0.28 | 0.05 | 0.05 | 0.04 | 0.14 | 0.12 | 0.15 | 0.00 | 0.07 |
| NCP15 | 0.13 | 0.18 | 0.43 | 0.47 | 0.08 | 0.09 | 0.03 | 0.03 | 0.12 | 0.13 | 0.01 | 0.06 |
| NCP16 | 0.34 | 0.18 | 0.53 | 0.69 | 0.15 | 0.17 | 0.17 | 0.26 | 0.13 | 0.26 | 0.14 | 0.23 |
| NCP17 | 0.99 | 0.99 | 0.97 | 0.96 | 0.99 | 0.99 | 0.99 | 0.97 | 0.98 | 0.96 | 1.00 | 0.99 |
| NCP18 | 0.74 | 0.63 | 0.87 | 0.91 | 0.68 | 0.84 | 0.53 | 0.88 | 0.54 | 0.75 | 0.58 | 0.83 |



**Fig. S1.** Mean (± SE) value of nature’s contribution to people for drylands and non-drylands for 1992 and 2018. Contributions were significantly lower in drylands in both years.

**Supplementary references**

Akhtar, M., Zhao, Y., Gao, G., Gulzar, Q., & Hussain, A. (2022). Assessment of spatiotemporal variations of ecosystem service values and hotspots in a dryland: A case-study in Pakistan. *Land Degradation & Development*, 33(9), 1383–1397. <https://doi.org/10.1002/ldr.4245>

Al Shamsi, Khalid Butti; Compagnoni, Antonio; Timpanaro, Giuseppe; Cosentino, Salvatore; Guarnaccia, Paolo (2018). A Sustainable Organic Production Model for “Food Sovereignty” in the United Arab Emirates and Sicily-Italy. Sustainability, 10(3), 620–. doi:10.3390/su10030620

Alcamo, J. et al. (2003). Ecosystems and human well-being: a framework for assessment/ Millennium Ecosystem Assessment. World Resources Institute, Washington, DC.

Aswani S, Lemahieu A, Sauer WHH. Global trends of local ecological knowledge and future implications. Plos One, 2018, 13: e0195440

Balmford A, Green JMH, Anderson M, et al. Walk on the wild side: Estimating the global magnitude of visits to protected areas. Plos Biol, 2015, 13: e1002074

Baur, P., Iles, A. Replacing humans with machines: a historical look at technology politics in California agriculture. Agric Hum Values 40, 113–140 (2023).

Borrelli P, Robinson DA, Fleischer LR, et al. An assessment of the global impact of 21st century land use change on soil erosion. Nat Commun, 2017, 8: 2013

Brim Box, J., Leiper, I., Nano, C., Stokeld, D., Jobson, P., Tomlinson, A., Cobban, D., Bond, T., Randall, D. and Box, P. (2022), Mapping terrestrial groundwater-dependent ecosystems in arid Australia using Landsat-8 time-series data and singular value decomposition. Remote Sens Ecol Conserv, 8: 464-476.

Brim Box, Jayne & Duguid, Angus & Read, R.E. & Kimber, R.G. & Knapton, A. & Davis, Jenny & Bowland, A.E. (2008). A review of groundwater-dependent ecosystems in central Australia: Oases of aquatic biodiversity. Journal of Arid Environments. 72. 1395-1413.

Brinkmann, K., Dickhoefer, U., Schlecht, E., & Buerkert, A. (2011). *Quantification of aboveground rangeland productivity and anthropogenic degradation on the Arabian Peninsula using Landsat imagery and field inventory data. Remote Sensing of Environment, 115(2), 465–474.*

Brinkmann, K., Patzelt, A., Dickhoefer, U., Schlecht, E., & Buerkert, A. (2009). Vegetation patterns and diversity along an altitudinal and a grazing gradient in the Jabal al Akhdar mountain range of northern Oman. Journal of Arid Environments, 73,1035−1045.

Butchart SHM, Walpole M, Collen B, et al. Global biodiversity: Indicators of recent declines. Science, 2010, 328: 1164-1168 2. Howard C, Flather CH, Stephens PA. A global assessment of the drivers of threatened terrestrial species richness. Nat Commun, 2020, 11: 993

Dale VH, Kline KL, Buford MA, et al. Incorporating bioenergy into sustainable landscape designs. Renew Sust Energ Rev, 2016, 56: 1158-1171

Daniel TC, Muhar A, Arnberger A, et al. Contributions of cultural services to the ecosystem services agenda. P Natl Acad Sci USA, 2012, 109: 8812-8819

Darvill, R., & Lindo, Z. (2015). Quantifying and mapping ecosystem service use across stakeholder groups: Implications for conservation with priorities for cultural values. *Ecosystem Services*, 13 (2015): 153-161.

Dicks LV, Breeze TD, Ngo HT, et al. A global-scale expert assessment of drivers and risks associated with pollinator decline. Nat Ecol Evol, 2021,

Eamus, D., Froend, R., Loomes, R., Hose, G. & Murray, B. (2006) A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Australian Journal of Botany, 54, 97–114.

Elbakidze M, Andersson K, Angelstam P, et al. Sustained yield forestry in sweden and russia: How does it correspond to sustainable forest management policy? Ambio, 2013, 42: 160-173

Fagan ME. A lesson unlearned? Underestimating tree cover in dryland biases global restoration maps. Global Change Biol, 2020, 26: 4679-4690

Feng XM, Fu BJ, Piao S, et al. Revegetation in china's loess plateau is approaching sustainable water resource limits. Nat Clim Change, 2016, 6: 1019-1022

Fischer, R A; Turner, N C (1978). Plant Productivity in the Arid and Semiarid Zones. Annual Review of Plant Physiology, 29(1), 277–317.

Fu BJ, Liu Y, Lu YH, et al. Assessing the soil erosion control service of ecosystems change in the loess plateau of china. Ecol Complex, 2011, 8: 284-293

Gapminder - Population v7 (2022); Gapminder - Systema Globalis (2022); HYDE (2017); United Nations - World Population Prospects (2022) – [with major processing](https://ourworldindata.org/grapher/population-density#sources-and-processing) by Our World in Data

Gherboudj, I., NaseemaBeegum, S. & Ghedira, H. Identifying natural dust source regions over the Middle-East and North-Africa: Estimation of dust emission potential. Earth-Sci. Rev. 165, 342–355 (2017).

Górriz-Mifsud, E., Ameztegui, A., González, J.R., Trasobares, A. (2022). Climate-Smart Forestry Case Study: Spain. In: Hetemäki, L., Kangas, J., Peltola, H. (eds) Forest Bioeconomy and Climate Change . Managing Forest Ecosystems, vol 42. Springer, Cham. <https://doi.org/10.1007/978-3-030-99206-4_13>

Gu Z, Gu L, Eils R, Schlesner M, Brors B (2014). “circlize implements and enhances circular visualization in R.” Bioinformatics, **30**, 2811-2812.

Hamed, Y., Hadji, R., Redhaounia, B. et al. Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterr J Environ Integr 3, 25 (2018)

Hanssen SV, Daioglou V, Steinmann ZJN, et al. The climate change mitigation potential of bioenergy with carbon capture and storage. Nat Clim Change, 2020, 10: 1023-1029

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E.S. Brondizio, J. Settele, S. Díaz, and H.T. Ngo (editors). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.3831673

IPBES. The assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services on pollinators, pollination and food production. Potts S.G., Imperatriz-Fonseca V. L., Ngo H. T. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany. 552 pages, 2016

Ives AR, Carpenter SR. Stability and diversity of ecosystems. Science, 2007, 317: 58-62

Kashyap, R. *et al.* (2023). Insect and Pest Management for Sustaining Crop Production Under Changing Climatic Patterns of Drylands. In: Naorem, A., Machiwal, D. (eds) Enhancing Resilience of Dryland Agriculture Under Changing Climate. Springer, Singapore. <https://doi.org/10.1007/978-981-19-9159-2_21>

Keeler BL, Hamel P, McPhearson T, et al. Social-ecological and technological factors moderate the value of urban nature. Nat Sustain, 2019, 2: 29-38

Lasway, J. V., Peters, M. K., Njovu, H. K., Eardley, C., Pauly, A., & Steffan-Dewenter, I. (2022). Agricultural intensification with seasonal fallow land promotes high bee diversity in Afrotropical drylands. *Journal of Applied Ecology*, 59, 3014–3026. <https://doi.org/10.1111/1365-2664.14296>

Le Houerou, Henry N. (2000). *Restoration and Rehabilitation of Arid and Semiarid Mediterranean Ecosystems in North Africa and West Asia: A Review. Arid Soil Research and Rehabilitation, 14(1), 3–14.*

Lelieveld J, Evans JS, Fnais M, et al. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature, 2015, 525: 367-371

Letourneau DK, Jedlicka JA, Bothwell SG, et al. Effects of natural enemy biodiversity on the suppression of arthropod herbivores in terrestrial ecosystems. Annu Rev Ecol Evol S, 2009, 40: 573- 592

Li W, Ciais P, Stehfest E, et al. Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale. Earth Syst Sci Data, 2020, 12: 789-804

Liu YF, Liu Y, Shi ZH, et al. Effectiveness of re-vegetated forest and grassland on soil erosion control in the semi-arid loess plateau. Catena, 2020, 195: 104787

Liu YX, Fu BJ, Wang S, et al. Global ecological regionalization: From biogeography to ecosystem services. Curr Opin Env Sust, 2018, 33: 1-8

Luck, G.W. (2007), The relationships between net primary productivity, human population density and species conservation. Journal of Biogeography, 34: 201-212.

Lund JF, Rutt RL, Ribot J. Trends in research on forestry decentralization policies. Curr Opin Env Sust, 2018, 32: 17-22

Martínez-Valderrama, J., Gartzia, R., Olcina, J. et al. Uberizing Agriculture in Drylands: A Few Enriched, Everyone Endangered. Water Resour Manage (2023). <https://doi.org/10.1007/s11269-023-03663-1>

Mayer PM, Reynolds SK, McCutchen MD, et al. Meta-analysis of nitrogen removal in riparian buffers. J Environ Qual, 2007, 36: 1172-1180

Millennium Ecosystem Assessment, 2005. Drylands Systems". Chapter 22 in: *Ecosystems and Human Wellbeing: Current State and Trends*, Volume 1. Island Press.

Morrison TH, Adger WN, Brown K, et al. Political dynamics and governance of world heritage ecosystems. Nat Sustain, 2020, 3: 947-955.

Morton, S.R., D.M. Stafford Smith, C.R. Dickman, D.L. Dunkerley, M.H. Friedel, R.R.J. McAllister, J.R.W. Reid, D.A. Roshier, M.A. Smith, F.J. Walsh, G.M. Wardle, I.W. Watson, M. Westoby, (2011). A fresh framework for the ecology of arid Australia, Journal of Arid Environments, 75, 313-329.

Nabhan, G. P., Riordan, E. C., Monti, L., Rea, A. M., Wilder, B. T., Ezcurra, E., Mabry, J. B., Aronson, J., Barron-Gafford, G. A., García, J. M., Búrquez, A., Crews, T. E., Mirocha, P., & Hodgson, W. C. (2020). An Aridamerican model for agriculture in a hotter, water scarce world. *Plants, People, Planet*, 2(6), 627–639.

Newman DJ, Cragg GM. Natural products as sources of new drugs over the 30 years from 1981 to 2010. J Nat Prod, 2012, 75: 311-335

O'Connor LMJ, Pollock LJ, Renaud J, et al. Balancing conservation priorities for nature and for people in europe. Science, 2021, 372: 856-860

Pascua Pa, McMillen H, Ticktin T, et al. Beyond services: A process and framework to incorporate cultural, genealogical, place-based, and indigenous relationships in ecosystem service assessments. Ecosyst Serv, 2017, 26: 465-475

Pimm SL, Jenkins CN, Abell R, et al. The biodiversity of species and their rates of extinction, distribution, and protection. Science, 2014, 344: 1246752

Pingzong Zhu, Guanghui Zhang, Hongxiao Wang, Hanyue Yang, Baojun Zhang, Lili Wang, (2021). Effectiveness of typical plant communities in controlling runoff and soil erosion on steep gully slopes on the Loess Plateau of China. Journal of Hydrology, 602, 126714, ISSN 0022-1694, <https://doi.org/10.1016/j.jhydrol.2021.126714>.

Potts SG, Imperatriz-Fonseca V, Ngo HT, et al. Safeguarding pollinators and their values to human well-being. Nature, 2016, 540: 220-229

Prăvălie, R. (2016). Drylands extent and environmental issues. A global approach, Earth-Science Reviews, 161, 259-278

Radhouane L (2013) Climate change impacts on North African countries and on some Tunisian economic sectors. J Agri Environ Intern Dev (JAEID) 107(1):101–113

Ramón Vallejo, V., Smanis, A., Chirino, E. *et al.* Perspectives in dryland restoration: approaches for climate change adaptation. *New Forests* **43**, 561–579 (2012). <https://doi.org/10.1007/s11056-012-9325-9>

Redmile-Gordon, M., A.S. Gregory, R.P. White, C.W. Watts (2020). Soil organic carbon, extracellular polymeric substances (EPS), and soil structural stability as affected by previous and current land-use. Geoderma, 363, 114143, ISSN 0016-7061, <https://doi.org/10.1016/j.geoderma.2019.114143>

Reis V, Hermoso V, Hamilton SK, et al. A global assessment of inland wetland conservation status. Bioscience, 2017, 67: 523-533

Renaud F, Sudmeier-Rieux K, Estrella M. The role of ecosystems in disaster risk reduction. Shibuya-ku, Tokyo 150-8925, Japan: United Nations University Press, 2013

Richards DR, Thompson BS, Wijedasa L. Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. Nat Commun, 2020, 11: ARTN 4260

Sahu, G., Mohanty, S. (2023). Assessment and Management of Soil and Water Erosion in Dryland Ecosystem. In: Naorem, A., Machiwal, D. (eds) Enhancing Resilience of Dryland Agriculture Under Changing Climate. Springer, Singapore. <https://doi.org/10.1007/978-981-19-9159-2_9>

Samuel J. Mayne, David I. King, Jeremy C. Andersen, Joseph S. Elkinton, Crop-specific effectiveness of birds as agents of pest control, Agriculture, Ecosystems & Environment, 348, 2023, 108395, ISSN 0167-8809, https://doi.org/10.1016/j.agee.2023.108395

Schulp CJE, Lautenbach S, Verburg PH. Quantifying and mapping ecosystem services: Demand and supply of pollination in the European union. Ecol Indic, 2014, 36: 131-141

Shahin, S.; Salem, M.A. The Challenges of Water Scarcity and the Future of Food Security in the United Arab Emirates (UAE). Natl. Resour. Conserv. 2015, 3, 1–6.

Siebert S, Kummu M, Porkka M et al (2015) A global data set of the extent of irrigated land from 1900 to 2005. Hydrol Earth Syst Sci 19:1521–1545.

Soga M, Gaston KJ. Extinction of experience: The loss of human-nature interactions. Front Ecol Environ, 2016, 14: 94-101

Stehfest E, van Zeist WJ, Valin H, et al. Key determinants of global land-use projections. Nat Commun, 2019, 10: 2166

Sterling SM, Ducharne A, Polcher J. The impact of global land-cover change on the terrestrial water cycle. Nat Clim Change, 2013, 3: 385-390

Still, C. J., J. A. Berry, G. J. Collatz, and R. S. DeFries, Global distribution of C3 and C4 vegetation: Carbon cycle implications, *Global Biogeochem. Cycles*, 17(1), 1006, doi:[10.1029/2001GB001807](https://doi.org/10.1029/2001GB001807), 2003.

Su Y, Gabrielle B, Makowski D. A global dataset for crop production under conventional tillage and no tillage systems. Scientific Data, 2021, 8: 33

Sweeney BW, Newbold JD. Streamside forest buffer width needed to protect stream water quality, hjabitat, and organisms: A literature review. J Am Water Resour As, 2014, 50: 560-584

Tandule, C.R., Gogoi, M.M., Kotalo, R.G. et al. On the net primary productivity over the Arabian Sea due to the reduction in mineral dust deposition. Sci Rep 12, 7761 (2022). <https://doi.org/10.1038>

Timpanaro, G.; Foti, V.T.; Spampinato, D. Organic Farming in Sicily: Analysis and perspectives through the main Productive Chains. Qual. Access Success 2013, 14, 157–164.

Wang YF, Bakker F, de Groot R, et al. Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. Build Environ, 2014, 77: 88-100

Worthington TA, Andradi-Brown DA, Bhargava R, et al. Harnessing big data to support the conservation and rehabilitation of mangrove forests globally. One Earth, 2020, 2: 429-443

Wuepper D, Borrelli P, Finger R. Countries and the global rate of soil erosion. Nat Sustain, 2019, 3: 51-55

Yu QY, You LZ, Wood-Sichra U, et al. A cultivated planet in 2010-part 2: The global gridded agricultural-production maps. Earth Syst Sci Data, 2020, 12: 3545-3572

Zhao M, Geruo A, Zhang JE, et al. Ecological restoration impact on total terrestrial water storage. Nat Sustain, 2021, 4: 56-62

Zhao MS, Running SW. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science, 2010, 329: 940-943

Zheng Y, Shen RQ, Wang YW, et al. Improved estimate of global gross primary production for reproducing its long-term variation, 1982-2017. Earth Syst Sci Data, 2020, 12: 2725-2746