Mapping the global distribution and conservation status of oases—ecosystems of pivotal biocultural relevance

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ABSTRACT

Background: Oases are azonal, highly productive, densely vegetated areas within drylands, often converted to agriculture, and characterized by significant biocultural diversity. Despite their importance, comprehensive information on the global distribution and biocultural diversity of oases has been lacking.

Methods: To address this gap, a detailed bibliographic search and random forest modeling were combined to create a global map of oases, with a focus on Asia and North Africa (ANA).

Results: In the ANA region, oases cover 1.5% of the dryland area and are populated by 150 million people, with an additional 268 million people living nearby and most likely being dependent on them. Globally, oases contain more than 8,200 vertebrate species, of which 13% are classified as threatened. However, less than 0.5% of their total area is currently under protection, making oases one of the least conserved ecosystems worldwide. These findings highlight the distinct biocultural, ecological, and geopolitical importance of oases, which are increasingly threatened by climate change and direct human impacts. Despite their significance, oases remain undervalued, emphasizing an urgent need for developing adaptative strategies to sustainably manage these pivotal ecosystems.

Subjects Conservation Biology, Ecology, Environmental Sciences, Coupled Natural and Human Systems, Spatial and Geographic Information Science
Keywords Biocultural diversity, Biodiversity, Conservation, Drylands, Heritage, Land use, Literature review, Machine learning

INTRODUCTION

Drylands cover almost 41 per cent of the global surfaces (excluding Antarctica) (*Vicente-Serrano et al., 2024*), harbor close to 40% of the total human population (*Reynolds et al., 2007*), and are home to species with unique traits, including important crops

(*Shachak et al., 2005*; *Buerkert et al., 2005*; *Buerkert, De Langhe & Al Khanjari, 2009*; *Davies et al., 2012*). Drylands exhibit scarce and unpredictable precipitation patterns (*Reynolds et al., 2007*), and evapotranspiration exceeds mean precipitation by a factor of 1.5 or more (*i.e.*, aridity index below 0.65; *Safriel et al., 2005*; *Davies et al., 2012*). Due to strong climatic constraints, drylands are very sensitive to global change (*Reynolds et al., 2007*); at the same time, they exhibit a high potential to alleviate its effects (*Li et al., 2015*). Drylands can contribute significantly to global net primary productivity (NPP) (*Lal, 2019*), despite being strictly controlled by water availability (*Maestre et al., 2016*). Simultaneously, irrigated arid lands have been identified as potentially large carbon sinks (*Li et al., 2015*).

Water is a scarce resource in drylands, with groundwater–often of fossil origin–as the main source (*Church, 1996*; *Faure, Walter & Grant, 2002*; *Gossel, Ebraheem & Wycisk, 2004*; *Ward, 2016*). Where water emerges to the surface, areas of high productivity in an otherwise arid or hyper-arid matrix are created, allowing oases to form and sustain (*Faure, Walter & Grant, 2002*; *Ling et al., 2013*; *Chen et al., 2022*).

Oases (*ouahe* in the demotic language of ancient Egypt; *Harper, 2023*) are defined in the literature as azonal (*Jia et al., 2004*) and highly productive (*Chen et al., 2022*) areas, often with permanent dense vegetation or converted into agricultural land (*de Haas & El Harradji, 2001*; *Liu, Wang & Xin, 2022*). Oases are characterized by a certain level of spatial isolation (*Zhang et al., 2012*; *Powell & Fensham, 2016*). They are considered as inland wetlands (*Ramsar, 2013*), also called "islands of fertility", with nutrient enrichment (*Chen et al., 2007*) as well as a unique microclimate (*Lü, An & Chen, 2004*) and vegetation structure (*Gebauer et al., 2007*; *Guezoul et al., 2013*).

Oases are characterized by distinct biocultural diversity (*Tydecks et al., 2023*), and they facilitate biological and cultural exchange through otherwise highly impermeable regions (*Shachak et al., 2005*; *Buerkert, De Langhe & Al Khanjari, 2009*; *Zhang et al., 2012*; *Tydecks et al., 2023*). Oases provide manifold ecosystem services such as high primary productivity, distinct bio- and agrodiversity, recreation values, as well as cultural services represented by local and traditional knowledge systems, cultural heritages, and sense of place (*Liang & Liu, 2017*; *Santoro, 2023*). Oases can serve as pivotal stepping stones, further facilitating biological (*Safriel et al., 2005*; *Davies et al., 2012*) and cultural diversity and evolution (*e.g.*, ancient Silk Road; *Zhang et al., 2012*).

Oases are of both natural or artificial origin (*Zu et al., 2003*). Naturally, they are either fed by rivers (linear oases), groundwater (isolated oases), temporary flow (source oases; *de Haas & El Harradji, 2001*) or fog (fog oases; *Moat et al., 2021*). Fog oases are found along the coasts of Chile, Peru and Namibia and rely on seasonal fog as their primary water source. They are "ecological islands"—ephemeral, woody, or herbaceous—hosting endemic plants and crop wild relatives (*Beresford-Jones et al., 2015*). However, artificial oases are classified as modern or traditional oases depending on the mode of agricultural management (*Santoro, 2023*).

Previous studies on oasis delineation have focused on single oases (*Yan & Guo, 2019*; *Mihi, Tarai & Chenchouni, 2019*) or on groups of oases within a single basin (*Wei et al., 2020*; *Lei et al., 2020*; *Ainiwaer, Ding & Kasim, 2020*). A variety of techniques has been employed to delineate oases, including image segmentation (*Liu, Wang & Xin, 2022*), the

U-Net model (*Salih, Hassaballa & Ganawa, 2021*), spatial entropy (*Huang et al., 2020*), random forest (*Wolf et al., 2016*; *Chen et al., 2022*) or manual digitalization (*Moat et al., 2021*). Previous research has applied land cover maps of drylands to identify oases as any land use other than bare land and permanent snow and ice (*Chen et al., 2024*).

The most prevalent methodology employed to delineate oases is the utilization of normalized difference vegetation index (NDVI) thresholds in arid regions (*Luedeling & Buerkert, 2008*; *Xie et al., 2018*; *Bai et al., 2023*; *Baioni, Fiantanese & Porta, 2024*; *Cui et al., 2024*). Research primarily covered the human-made expansion of oases (*Chen et al., 2022*) or focused on their hydrology and the related water risks (*Liu & Shen, 2018*; *Huang et al., 2020*). Typically, comprehensive studies about oases distribution and delineation are limited to one (*Luedeling & Buerkert, 2008*; *Li, Feng & Guo, 2008*; *Ait-El-Mokhtar et al., 2020*; *Chen et al., 2022*; *Liu, Wang & Xin, 2022*) or two countries (*Moat et al., 2021*), partly due to their complex and diverse origin and typology (*Luedeling & Buerkert, 2008*).

Recent studies have contributed significantly in mapping the global distribution of oases. Two of these, either compiled a vast number of observations of oases, focusing on springs in drylands (*Fensham et al., 2023a*) or applied remote sensing techniques to track oasis trends over recent decades (*Cui et al., 2024*). Despite these advancements, there remains a critical lack of comprehensive and open-access data, on oasis biodiversity, conservation value and protection levels. This is of major concern considering a high degree of endemicity (*Falcón-Brindis, Rodríguez-Estrella & Jiménez, 2019*; *Falcon-Brindis & León-Cortés, 2023*; *Fensham et al., 2023b*) in oases.

There is a pressing need to advance conservation strategies that incorporate biological and cultural diversity, *i.e.*, biocultural diversity, which is an emerging approach advocated by global organizations such as *UNESCO & UNEP (2002)*, *Millennium Ecosystem Assessment (2005)* and, more recently, by *IPBES (2019)*. Despite a growing interest in the interplay of human and nature, recent projects (*Fensham et al., 2023a*; *Cui et al., 2024*) focus mainly on the role of hydrology for the conservation of oases. Although being of crucial importance, our knowledge about the cultural values of oases and their multifaceted linkages with biological diversity remains fragmentary.

Finally, current analyses on oases are lacking comprehensive information on socio-economic aspects. While there is clear evidence that the majority of people in arid and hyper-arid areas lives in or adjacent to oases, we identified only one study on human population density in and around oases. In northern China, oases cover less than 5% of the entire territory but provide habitat for more than 90% of the respective human population (*Li, Li & Wang, 2007*).

Our goal is to establish a comprehensive data and knowledge base that covers the contemporary distribution, delineation and status of oases, globally, and specifically in the ANA (Asia and North Africa) region. We aim at providing–spatially explicit–information on fundamental environmental, biological and cultural characteristics of oases. To achieve this, we combined an empirical assessment with a modelling approach (*i.e.*, a detailed bibliographic search with Random Forest modeling) to quantify i) the spatial distribution and delineation of oases, ii) their species diversity and conservation status, and iii) their human population density, land use, and overall cultural relevance. We are convinced that

this comprehensive work may increase awareness about the pivotal biological and cultural importance of oases, stimulate interdisciplinary research in and of oases, and support the development and implementation of adequate conservation and adaptation measures.

MATERIALS AND METHODS

To capture the current global distribution of oases and to create a comprehensive map of oases, geographic data was compiled by an extensive bibliographic search on studies of oases and by a citizen science photo project. This empirical work was integrated into a statistical modeling approach that is based on indicators derived from remote sensing data. This allowed us not only to delineate the oases identified in the literature but also to predict the location of all oases not covered by scientific publications (Fig. 1).

Bibliometric search

The literature search on the location and characteristics of oases was constraint in a meaningful way by selecting countries that, based on climatic conditions, are potential candidates for containing oases. Therefore, all countries with arid or hyper-arid areas (*Sorensen, 2007*), indicated by an average aridity index lower than 0.2, were selected (Fig. 2) by overlapping available dryland data (*UNEP-WCMC, 2007*) with global country boundaries (*QGIS, 2021*; version 3.22.0-Bialowieza). This yielded a list of 59 countries (Table 1). In the next step, bibliographical research in 'Web of Science' was confined by the word "oasis" (same spelling in English, French, and Spanish; *i.e.*, "oasis" (All Fields) AND <country name in English> (All Fields)). We considered all articles published until 2023. For China, Spain, and the United States of America, we selected the first 689 articles found (*i.e.*, the most accurate results in the bibliographic research). A total of 689 was selected as the maximum number of articles per country because it was the number of articles reviewed for Egypt, the country with the fourth highest number of research articles found in the bibliographic research. Hence, the time required for reviewing was limited without losing significant information, considering that for China, Spain, and the United States of America we found 6,023, 834, and 2,967 articles, respectively.

Every abstract in all languages found (*i.e.*, English, French, Spanish, German, and Chinese) was processed and, if it included research about oases (*e.g.*, specific studies on the functioning of the oasis) or was based on an oasis (*e.g.*, medical research conducted in an oasis), the article was reviewed in its entirety to obtain further information. We annotated every reviewed article to avoid duplicates. We recorded the coordinates of the oasis listed in a given article, as well as the name of the oasis. If no names or coordinates were provided, we used Google Maps to determine the location and/or the name of the oasis. Every time an oasis already included in our database was found in the bibliography, we used the same coordinates and name as before, to avoid duplicates. We annotated relevant bibliographic information about every article and a summary of topics (*i.e.*, agronomy, archaeology, biodiversity, botany, climate, ecology, genetics, geology, human health, human impact, hydrology, ornithology, paleontology, remote sensing, among others, aims, methodology, and results (Table S1).
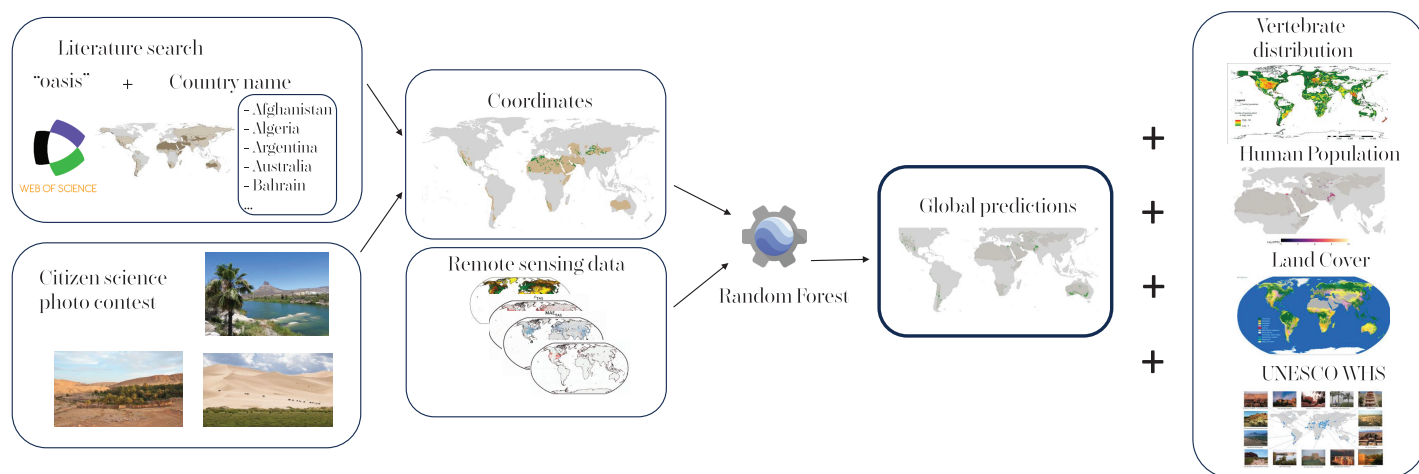
Figure 1 The methodology employed in the study. Showcasing the sequential progression through data acquisition (left), preliminary distribution of oases based on data (left-middle), model projections (right-middle) resulting in a final map of sites for oases, and overlap with site characteristics regarding biodiversity, human population density and cultural meaning (right). Full-size ◩ DOI: 10.7717/peerj.18884/fig-1
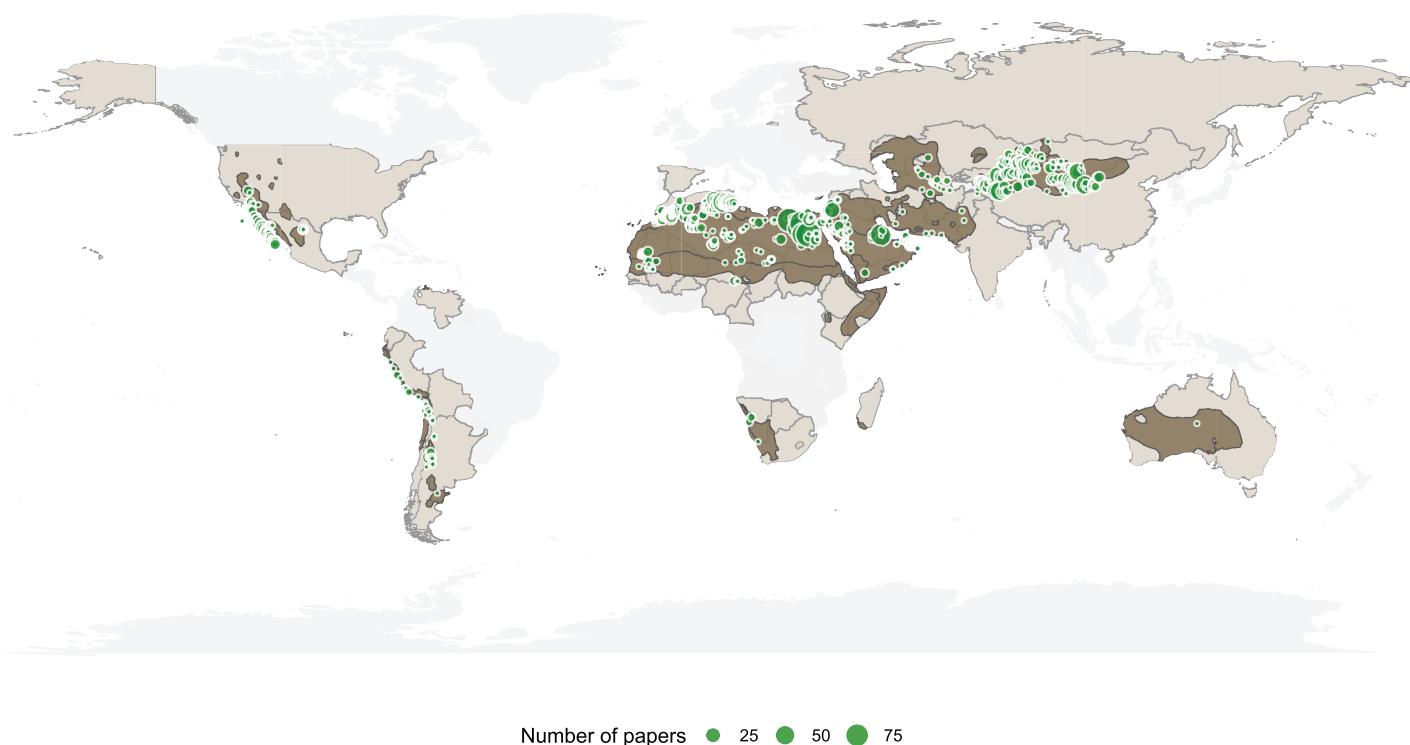

Number of papers ● 25 ● 50 ● 75

Figure 2 Research carried out on individual oases based on available literature, scaled to the number of articles. Global distribution of arid and hyper-arid areas (aridity index value: <0.2) in brown and countries included in our bibliographic research in light brown. A high-resolution version of this figure is available in the Supplemental Materials. Full-size ◩ DOI: 10.7717/peerj.18884/fig-2

Coordinates obtained by a citizen science photo contest project (*WOase: Citizen science to delineate world oases*) were also included in the database for creating the global map. All participants were researchers who provided photographs and coordinates of oases from their study sites (for more information, see: https://oasen.sgn.one/). Coordinates supplied

Table 1 Countries containing arid and hyper-arid regions. Number of articles found in the bibliographic research (WoS, Web of Science), number of articles finally included in the database, and number of oases per country identified by literature. Some articles covered several countries. The total count of articles in the WoS, those included in the database, and the overall number of identified oases are provided.

Country	Papers in WoS	Papers in database	Oases in database	Country	Papers in WoS	Papers in database	Oases in database
Afghanistan	6	0	0	Mali	20	1	0
Algeria	153	84	154	Mauritania	20	9	79
Argentina	149	22	33	Mexico	249	22	78
Australia	649	8	1	Mongolia	207	50	24
Bahrain	3	0	0	Morocco	238	85	174
Bolivia	8	1	0	Niger	27	5	9
Botswana	10	0	0	Nigeria	55	8	3
Burkina Faso	10	0	0	Oman	95	38	68
Cameroon	6	0	0	Pakistan	156	8	5
Cape Verde	7	0	0	Palestine	8	0	1
Chad	18	3	15	Peru	50	7	42
Chile	162	9	61	Qatar	17	0	0
China	689	442	198	Russia	211	1	0
Cyprus	11	4	0	Saudi Arabia	275	48	71
Djibouti	2	0	0	Senegal	10	1	0
Ecuador	5	0	0	Somalia	0	0	0
Egypt	689	350	40	Somaliland	0	0	0
Eritrea	5	1	0	South Africa	193	12	0
Ethiopia	34	1	0	Spain	689	16	0
India	505	4	0	Sudan	43	16	0
Iran	71	1	3	Syria	18	3	4
Iraq	18	1	0	Tunisia	392	154	132
Israel	172	24	9	Turkmenistan	26	4	12
Jordan	112	29	2	UAE	35	3	16
Kazakhstan	118	4	1	USA	689	42	23
Kenya	23	2	0	Uzbekistan	61	8	8
Kuwait	18	0	0	Venezuela	7	0	0
Kyrgyzstan	53	4	0	Western Sahara	10	1	0
Libya	53	27	27	Yemen	16	1	4
Madagascar	7	0	0	TOTAL	5,770 (7,574)	1,573	1,344

by the researchers who participated in the photo contest were double-checked to avoid location errors. Finally, articles provided by researchers but not found in the bibliographic research were included in the database but were not used to calculate the maps.

Mapping oases globally

To obtain a global map of oases, we carried out a three-step procedure: First, we trained random forest models (hereinafter RF) in detecting oases using our collected coordinate dataset in combination with remote sensing maps. RF is a machine-learning algorithm for

classification that partitions data into subsets (regression trees) and averages the results. For classification, RF uses *features* (here, our list of remote sensing indicators) and their corresponding class *labels* (here, presence or absence of oases). For the RF class labels, coordinates of each oasis were used as presence points. We only applied one pair of coordinates and a single name per oasis to avoid pseudoreplication when training the model (1,145 in total; Fig. 1). A total of 1,145 pseudo-absences were randomly generated with the 'randomPoints' function of the 'dismo' package (*Hijmans et al., 2021*). The RF features reflect vegetation and climate conditions (in line with the definition of oases extracted from our bibliographic research, see Table S2). Other variables such as elevation or slope were considered originally, but were removed after showing non-substantial predictive power. Vegetation conditions were represented using the median NDVI values based on the Landsat 8 Collection 1 Tier 1 32-Day NDVI Composites between 2020-01-01 and 2021-12-31, using the software Google Earth Engine (*Gorelick et al., 2017*) with the 'median' function. For the climatic conditions, we selected 'Actual evapotranspiration' (aet), 'Precipitation accumulation' (pr), and 'Reference evapotranspiration' (pet), 'Maximum temperature' (tmmx), 'Climate water deficit' (def), 'Palmer Drought Severity Index' (pdsi), 'Soil moisture' (soil), and 'Vapor pressure deficit' (vpd) bands from TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces (*Abatzoglou et al., 2018*). The 'Global Aridity Index' (b1) was extracted from *Zomer & Trabucco (2019a)*, and Landsat eight Collection 1 Tier 1 32-Day NDVI Composites (NDVIMedian2) were also used (Table 2). The function 'addBands' was used to train the model. The resulting image containing four bands was cropped to the area of interest (global land surface) with the 'clip' function, and subsequently, only areas with median values of NDVI higher than 0.2 were selected creating a mask with the 'gt' function and then using the 'updateMask' function over the image including the predictors as bands. This threshold was implemented to eliminate bare soil in deserts while ensuring that no oases was excluded which we had identified from our bibliographic research. It was established after conducting several tests varying the threshold NDVI value to enhance the accuracy of the RF model capturing the global distribution of oases. Similar thresholds have been used previously to delineate oases (*Cui et al., 2024*).

In the next step we trained the final RF with the 'ee.Classifier.smileRandomForest' function with a grain size of 100 m. A total of 80% of the coordinates for absence or presence were selected with the 'randomColumn' and 'filter' functions to build the RF model. The remaining 20% of the coordinates were used for testing overall accuracy after training the model. We created 1,000 decision trees to train the model. We obtained a confusion matrix, and the overall accuracy for the training and validation sample. The overall accuracy value of Random Forest classification was 1.00, while validation accuracy was 0.99. The kappa value of the model was 1.00. Relative importance of predictors ranged from 322 to 479, with 'Global Aridity Index', 'Actual evapotranspiration', 'Precipitation accumulation', and 'NDVI' being the most important bands (Table S3). The out-of-bag error estimate was 0.04.

In the last step, we predicted further possible oases with the final RF model, allowing to identify additional oases that were not subject of the reviewed research so far.

Table 2 Random forest training metrics data, detailing data type, source, resolution.

Metric	Acronym	Data type	Resolution	Time	Source	URL
Median NDVI	NDVI Median2	Quantitative	30 m	2020-01-01 to 2021-12-31	Landsat 8 Collection 1 Tier 1 32-Day NDVI Composites	https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_COMPOSITES_C02_T1_L2_32DAY_NDVI#description
Global aridity index	b1	Quantitative	1,000 m	1970–2000	Zomer & Trabucco (2019b)	https://gee-community-catalog.org/projects/ai0/
Actual evapotranspiration	aet	Quantitative	4,638.3 m	2018-01-01 to 2021-12-31	Abatzoglou et al. (2018)	https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE
Climate water deficit	def					
Palmer drought severity index	pdsi					
Reference evapotranspiration	pet					
Soil moisture	soil					
Maximum temperature	tmmx					
Vapor pressure deficit	vdp					

ANA region: in-depth analysis

To evaluate the importance of oases in terms of species diversity, human population density, and conservation status, an extensive case study was conducted for countries of Asia and North Africa. This selection was made based on the representativeness of these countries over the total number of studies carried out on oases (covering 85% of all coordinates obtained). The total area of the oases derived *via* remote sensing was estimated in Google Earth Engine for every country using the 'area' function. Shapefiles of oases of every country were exported with the 'Export.table.toDrive' function at a km scale.

Species richness and conservation status

Shapefiles of global oasis distribution were used to estimate the potential number of mammal, reptile, amphibian, and bird species whose ranges include oases. Digital Distribution Maps from the IUCN Red List of Threatened Species (IUCN, 2022) and bird species distribution maps of the world from BirdLife (2022) were overlapped with the 'Intersection' function of QGIS to obtain a list of species whose distribution ranges include any of our predicted oases. Also, the layers were overlapped with the country boundaries to obtain a list of species per country. Maps of protected areas of the world were obtained from UNEP-WCMC & IUCN (2023), and protected areas from IUCN categories I to VI were selected. The intersection of protected areas of the world and oasis predictions generated with RF was made using the 'Intersection' function of QGIS. The result was dissolved at country level with the 'Dissolve' function, and the protected area was calculated at country level with the 'area' function.

Human population, land use, World Heritage sites

Human population data was obtained from WorldPop Global Project Population Data with a 100 m × 100 m resolution between 2020-01-01 and 2020-12-31, overlaying our shapefiles of global oasis distribution using the 'sum' function. Buffers of 1 and 10 km were created with the 'buffer' function, and human population was also estimated at country level for both geometries.

The relative proportion of land cover classes was extracted for global oases prediction from Copernicus Global Land Cover Layers: CGLS-LC100 Collection 3 (*Buchhorn et al., 2020*) between 2018-01-01 and 2019-12-31 for every category (*i.e.*, 'tree cover,' 'crop cover,' 'grass cover,' 'shrub cover,' 'urban cover,' and 'bare cover') at country level with 1,000 m resolution. The script can be accessed in the Supplemental Script. Principal component analyses were used to characterize oasis land cover at country level with the 'prcomp' function, after scaling variables in the R software (*R Core Team, 2020*).

Coordinates of all World Heritage sites were downloaded, and a buffer of 10 km was created around every point with the 'buffer' function of QGis with 0.0899° diameter. The results were overlapped with the 'Intersection' function to obtain the list of WH UNESCO sites inside or near an oasis.

RESULTS

Bibliographic search

The bibliographic search resulted in a total of 5,573 articles (Table S4). Of those, 1,566 articles provided information on a particular oasis or a group of oases and were therefore further considered in our analyses (Table S1). Based on these publications, a total of 1,037 individual oases from 30 countries were identified. An additional 223 oases were provided by 19 researchers who participated in a global citizen science project (https://oasen.sgn. one/). Finally, 92 articles, which were not identified by the literature browser used, were provided by colleagues, adding 84 additional oases to the database. Hence, a total of 1,344 oases were included in the database, derived from 1,658 publications (Table 1; Fig. 2; Table S5). For some oases, information regarding location was lacking, and it was not possible to find them in any other source.

Articles covered the period 1974 to 2023 and comprised 43 different topics, dominated by 'agronomy' (303 articles), 'hydrology' (295 articles), 'paleontology' (163 articles) and 'remote sensing' (112 articles; Fig. S1). Articles were published in 747 different journals, with most articles in 'Journal of African Earth Sciences' (54 articles), 'Environmental Earth Sciences' (45 articles), 'Arabian Journal of Geosciences' (44 articles) and 'Journal of Arid Environments' (37 articles). A total of 1,209 articles included only one oasis, while 166, 83, and 34 articles contained information about 2, 3, and 4 different oases, respectively. The highest number of oases were covered by *Moat et al. (2021)* with 85 oases from Peru and 30 from Chile, *Li, Feng & Guo (2008)* with 68 oases from China, and *Ait-El-Mokhtar et al. (2020)* with 40 oases from Morocco. The country with the highest number of oases included in the database was China (193 oases), followed by Morocco (174), Algeria (147), and Tunisia (127). The most frequently studied oases were located in Egypt: 'Kharga oasis'

(included in 94 articles), 'Bahariya oasis' (92 articles), and 'Siwa oasis' (83 articles). The northernmost oasis was identified in Mongolia ('Baruun Tooroi'; 50.03°N), the southernmost oasis in Argentina ('Arroyo Telsén'; −42.47°S).

Mapping oases globally

The results of the Random Forest validation error matrix indicated 174 true positives, no true negatives, one false positive, and 43 false negatives. This yielded an overall accuracy rating of 0.99 for the classifier. Random Forest modeling suggested that oases are spread across all drylands except Antarctica (Fig. 3). The basins of the rivers Nile, Euphrates, and Indus are covered by a high density of oases. The southern part of South America and southern Australia also harbor a high density of oases, concentrated along the margins of drylands. Inner Asia contains a high number of scattered oases, very similar to North America. Finally, many small oases were predicted for North-West Africa, particularly along the margin of the Sahara Desert. A vector version of the global map of oases at a resolution of 1 km can be accessed as Supplemental Material (Map).

ANA region: in-depth analysis

Oases of Asia and North Africa (ANA; Fig. 4) cover a total area of 402,117 km^2 (assessment: 2021) according to the predictions of our Random Forest model (Table 3). The total area of oases per country ranges from less than 9 km^2 (Bahrain) to more than 123,000 km^2 (Pakistan). The relative proportion of oases in terms of area is 0.68% (all countries combined in the ANA region), ranging from 0.01% (Cameroon) to 14.20% (Pakistan) of the respective country. In the ANA region, arid and hyper-arid areas cover in total 20 million km^2 (40% of total area of the ANA region), of which 1.52% are covered by oases.

Species richness and conservation status

A total of 8,281 mammal, reptile, amphibian, and bird species were identified in the predicted oases globally. In China, 2,673 vertebrate species were recorded for oases, compared to 84 species for oases in Cape Verde. According to the IUCN red list, a total of 470, 450, and 220 of these vertebrate species are considered Vulnerable, Endangered, or Critically Endangered, respectively (Table S6).

Overall, only 0.32% of the total area of oases is protected to date; in 25 out of 43 countries, oases are not protected at all (*i.e.*, <0.01% of area of oases in each country; Table 3, Table S7). The protected area peaks in Kenya (14.96% of oases protected), Mongolia (9.27%), and Senegal (5.90%).

Human population, land use, and World Heritage sites

In the ANA region, a total of 150 million people lives in oases (Table 3), primarily in Pakistan (60 million), Egypt (50 million), and Iraq (more than 7 million). However, few people live in oases in Cameroon (less than 400 people), Cape Verde (about 1,700 people), and Mongolia (about 2,000 people). In Egypt, 61% of the total human population live in oases, in Morocco 35% of all people. The human population adjacent to oases (*i.e.*, within a perimeter of 1 km around each oasis) amounts to 64 million people (ANA region), and an
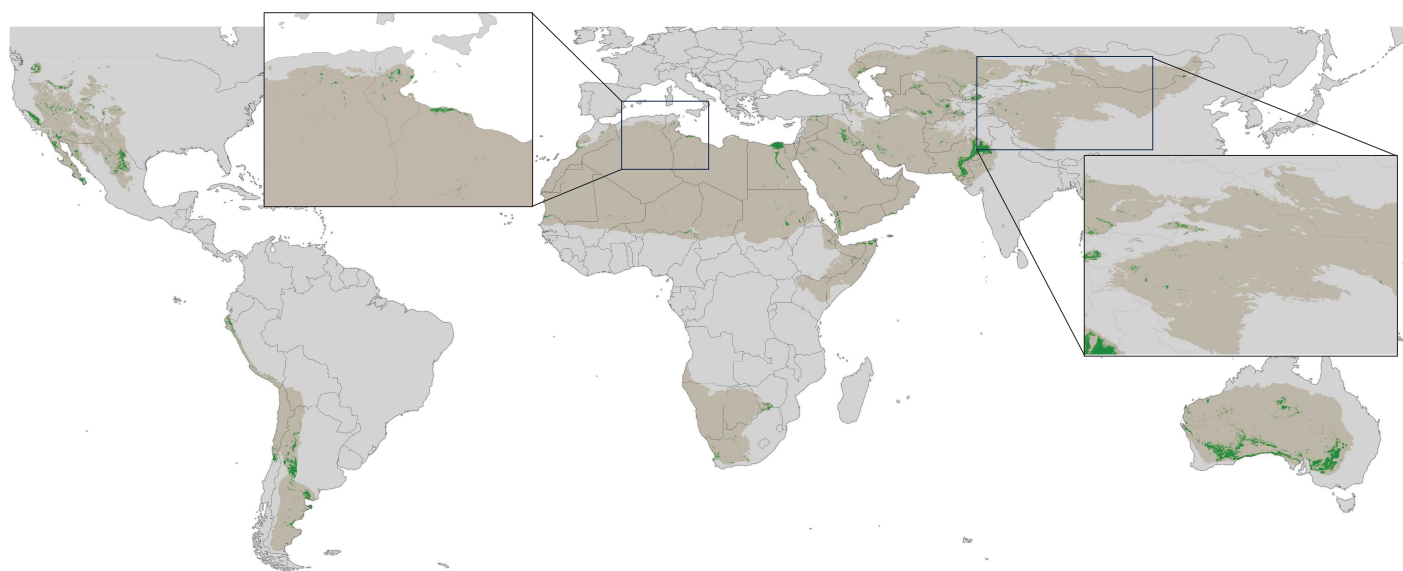
Figure 3 Global distribution of arid and hyper-arid areas (aridity index value: <0.2; in brown) and contemporary distribution of permanent densely vegetated areas (i.e., oases) in arid and hyper-arid areas predicted by the Random Forest model (in green). Subplots are generated for North Africa and China. A high-resolution version of this figure is available in the Supplemental Materials.
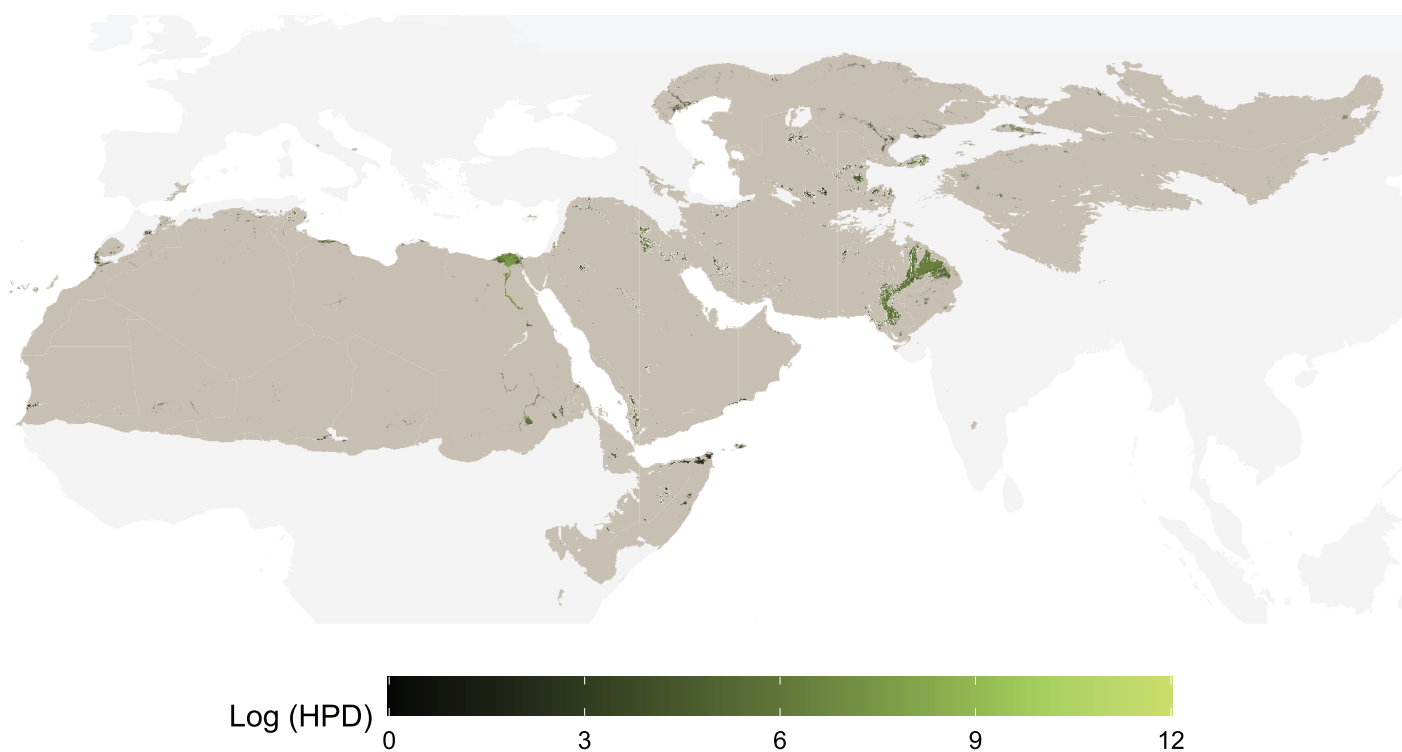Full-size 🖼 DOI: 10.7717/peerj.18884/fig-3

Figure 4 Contemporary (by 2021) distribution of oases as indicated by the Random Forest model for Asia and North Africa. Colors represent human population density (HPD) per square kilometer in logarithmic scale. Global distribution of arid and hyper-arid areas (aridity index value: <0.2) in brown.
Full-size 🖼 DOI: 10.7717/peerj.18884/fig-4

Table 3 Countries of the ANA region (Asia and North Africa). Total area of oases, percentage in terms of country area covered by oases, human population within oases and proportion (%) of the total population of country, human population within a 1 and 10 km perimeter of oases; relative proportion (%) of oases per country listed as protected.

Country	Area (km²)	% area of the country	Population	% of population of the country	Population 1 km buffer	Population 10 km buffer	% protected
Afghanistan	5,780	0.90	1,725,714	6.60	3,376,453	8,693,653	1.82
Algeria	1,953	0.08	336,046	0.88	1,122,439	4,072,630	0.00
Bahrain	9	1.15	13,024	0.65	113,602	1,476,150	0.00
Cameroon	25	0.01	389	0.00	1,181	7,712	0.00
Cape Verde	19	0.47	1,718	0.38	13,862	260,321	0.00
Chad	5,250	0.41	69,900	0.49	150,776	777,656	0.00
China	12,239	0.13	2,140,084	0.17	6,822,464	26,904,128	0.19
Cyprus	120	1.32	23,646	2.05	110,413	616,225	4.08
Djibouti	28	0.13	7,769	0.77	34,622	563,602	0.00
Egypt	40,214	4.09	50,605,930	61.49	62,353,484	80,239,386	0.01
Eritrea	425	0.35	16,548	0.46	41,577	233,450	0.68
Ethiopia	5,258	0.46	172,275	0.19	336,141	1,236,715	2.02
India	13,275	0.42	2,575,963	0.21	4,684,631	13,206,803	0.00
Iran	19,212	1.18	3,735,907	5.42	10,589,507	33,164,713	0.15
Iraq	19,845	4.54	7,628,487	19.95	13,217,540	23,592,983	1.29
Israel	199	0.96	16,200	0.21	78,643	2,369,305	0.00
Jordan	486	0.54	110,332	1.81	292,873	2,622,608	0.00
Kazakhstan	20,447	0.75	239,027	1.53	661,980	2,101,884	0.28
Kenya	718	0.12	72,303	0.15	255,877	835,660	14.96
Kuwait	93	0.54	11,783	0.38	41,136	406,209	0.00
Kyrgyzstan	647	3.27	135,473	2.66	367,321	2,239,648	0.57
Libya	4,553	0.28	827,363	13.97	3,670,778	3,670,778	0.00
Mali	1,932	0.15	89,880	0.45	241,803	1,075,611	0.00
Mauritania	2,003	0.19	50,224	1.31	141,247	785,780	0.00
Mongolia	2,191	0.14	2,004	0.07	8,978	96,554	9.27
Morocco	7,002	1.69	1,072,358	34.99	3,113,708	6,813,969	0.50
Niger	3,020	0.26	165,513	0.81	341,361	1,715,058	0.00
Nigeria	4,027	0.44	205,542	0.11	327,819	827,020	0.00
Oman	2,914	0.94	265,052	8.33	596,047	2,310,171	0.00
Pakistan	123,343	14.12	60,213,412	30.27	77,346,330	105,704,443	0.00
Palestine	75	1.30	26,978	0.88	67,356	355,471	0.00
Qatar	41	0.36	6,412	0.11	44,927	2,042,803	0.00
Russia	5,568	0.03	55,906	0.13	250,986	796,131	0.00
Saudi Arabia	11,326	0.59	638,582	2.01	1,910,443	12,478,069	1.60
Senegal	1,526	0.77	144,258	1.03	291,706	751,398	5.90
Somalia	14,642	2.30	123,630	1.30	218,977	1,069,347	0.00
Sudan	12,609	0.69	2,249,991	6.19	4,313,434	11,160,534	0.00
Syria	3,826	2.04	1,237,517	5.39	2,962,019	10,512,480	0.00
Tunisia	2,878	1.85	367,626	3.70	948,857	2,691,929	0.00

| Table 3 (continued) | | | | | | | |
Country	Area (km^2)	% area of the country	Population	% of population of the country	Population 1 km buffer	Population 10 km buffer	% protected
Turkmenistan	12,797	2.62	1,278,836	15.05	3,390,680	7,462,666	0.52
UAE	326	0.46	195,776	2.50	914,134	6,095,182	0.84
Uzbekistan	23,474	5.24	6,812,989	23.69	1,193,065	17,148,561	0.34
Yemen	12,886	2.83	3,487,567	13.38	5,691,619	13,482,142	0.00
TOTAL	401,945	0.68	150,045,048	4.16	214,212,885	418,530,517	0.32

additional 214 million people live between 1 km and 10 km around oases; therefore, 418 million people live in or adjacent to oases (9% of the total human population of the ANA region). Average human population density in oases is 375 people per km^2, and density exceeds 1,040 people per km^2 when people adjacent to oases (*i.e.*, people living within a perimeter of 10 km of an oasis) are included, assuming that they depend on the resources provided by oases. Hence, oases are among the most densely populated areas globally, outside of urban areas.

Globally, according to Copernicus Global Land Cover maps, oases are covered by grasses (24.4%), followed by bare land (21.4%), and urban areas (21.4%; Fig. 5B). Components 1 and 2 of the Principal Component Analysis (PCA) from the percentage of each Land Cover type represent 42% and 24% of the total variation, respectively (cumulative percentage of 66.5%). PCA component 1 was positively correlated with the percentage of crops and urban areas, and inversely correlated with the percentages of trees, shrubs, and grasses. Therefore, this axis can be named the 'Pristine-Managed' gradient (Fig. 5A). PCA component 2 was positively correlated with the percentage of trees and inversely correlated with the proportion of grasses. Therefore, the second axis was named 'Herbaceous-Forested' gradient (Fig. 5C).

A total of 75 UNESCO World Heritage sites (WHs)–65 cultural, eight natural, and two both natural and cultural WHs–were identified in or adjacent to oases. 'Willandra Lakes Region' and 'The Ahwar of Southern Iraq' are of both cultural and natural importance. Iran contains 9 WHs, and Egypt has 5 WHs. Egypt's WHs include 'Historic Cairo', 'Abu Mena', 'Memphis and its Necropolis', 'Nubian Monuments', and 'Thebes with its Necropolis' (Fig. 6).

DISCUSSION

Globally, oases are unique systems that occur in most drylands, where they form key nodes for humans and nature alike. However, until now, a comprehensive overview of the distribution, delineation and biocultural diversity of oases has been missing. In this study, we identified a total of 1,344 oases from 30 different countries, based on 1,657 relevant research articles. In Asian and North African (ANA) countries, oases cover in total about 400,000 km^2, corresponding to 1.5% of the arid and hyper-arid area of this region. To date, more than 8,200 vertebrate species have been recorded in oases globally, with more than
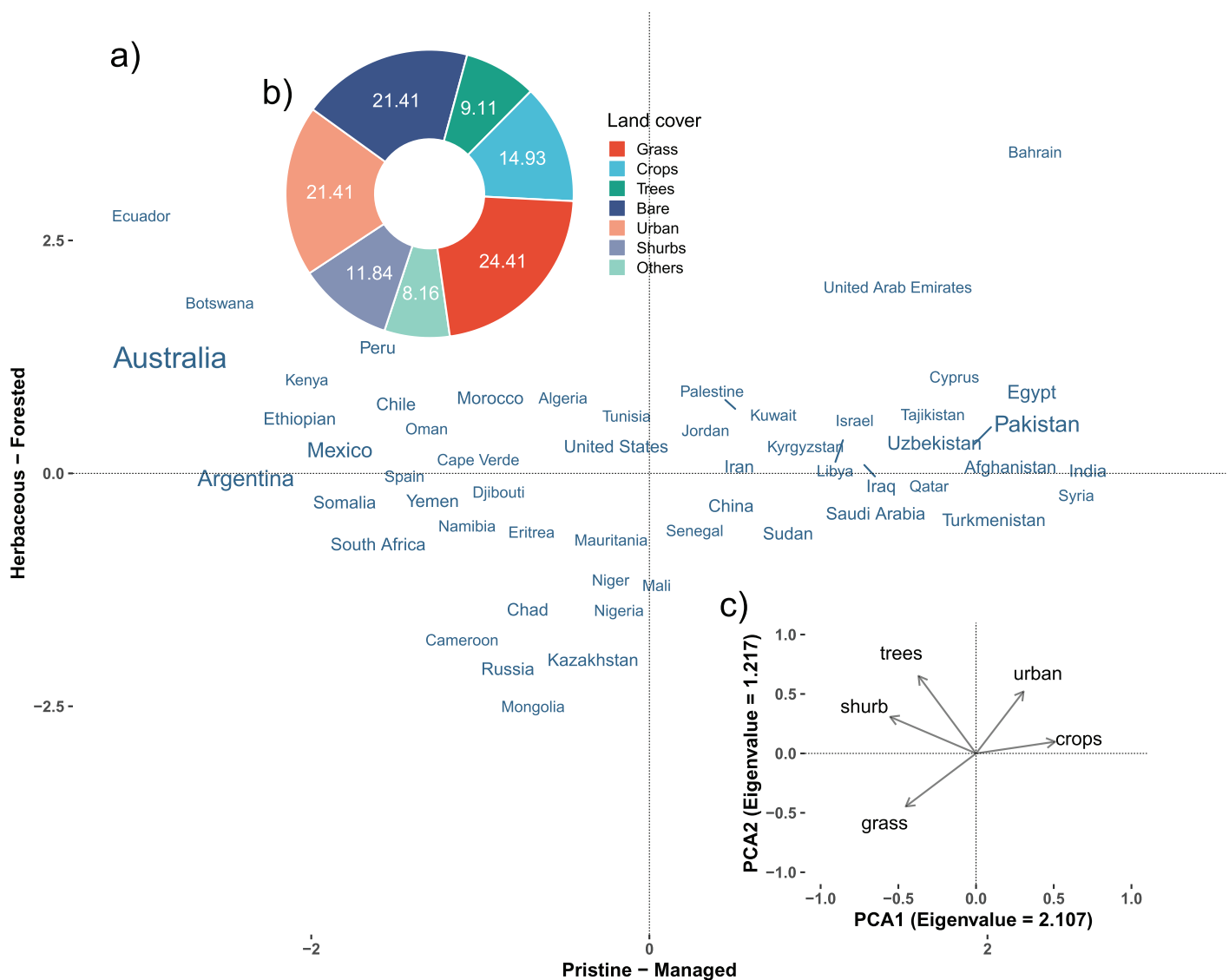
Figure 5 Land cover (%) of all oases. Land cover (%) of all oases combined, and principal component analysis (PCA) based on land cover of the oases of each country combined (proportion of variance/standard deviation axis 1 0.42/1.451, axis 2 0.24/1.103). (A) Results of PCA representing the ordination of countries according to the two first components of the analysis. Text size represents the area of oases in each country. Axis 1 relates to the degree of management (related to crops and urban areas), axis 2 reflects the proportion of trees or grasses in oases. (B) Percentage of land cover on a global scale. (C) Biplot scores of the variables of land cover in the PCA. Full-size 🖼 DOI: 10.7717/peerj.18884/fig-5

13% of them listed as threatened. At the same time, less than 0.5% of the total area of oases is protected.

In the ANA region, over 150 million people inhabit oases, and up to 400 million people are most likely dependent on oases. This reflects the high productivity and overall relevance of oases in an otherwise harsh environment. Moreover, 75 UNESCO World Heritage sites are located in or adjacent to oases, which underpins the cultural importance of this landform through history.

A key challenge is to develop an inclusive definition of oases, which may have constrained a global inventory and synoptic research of oases. Based on extensive literature
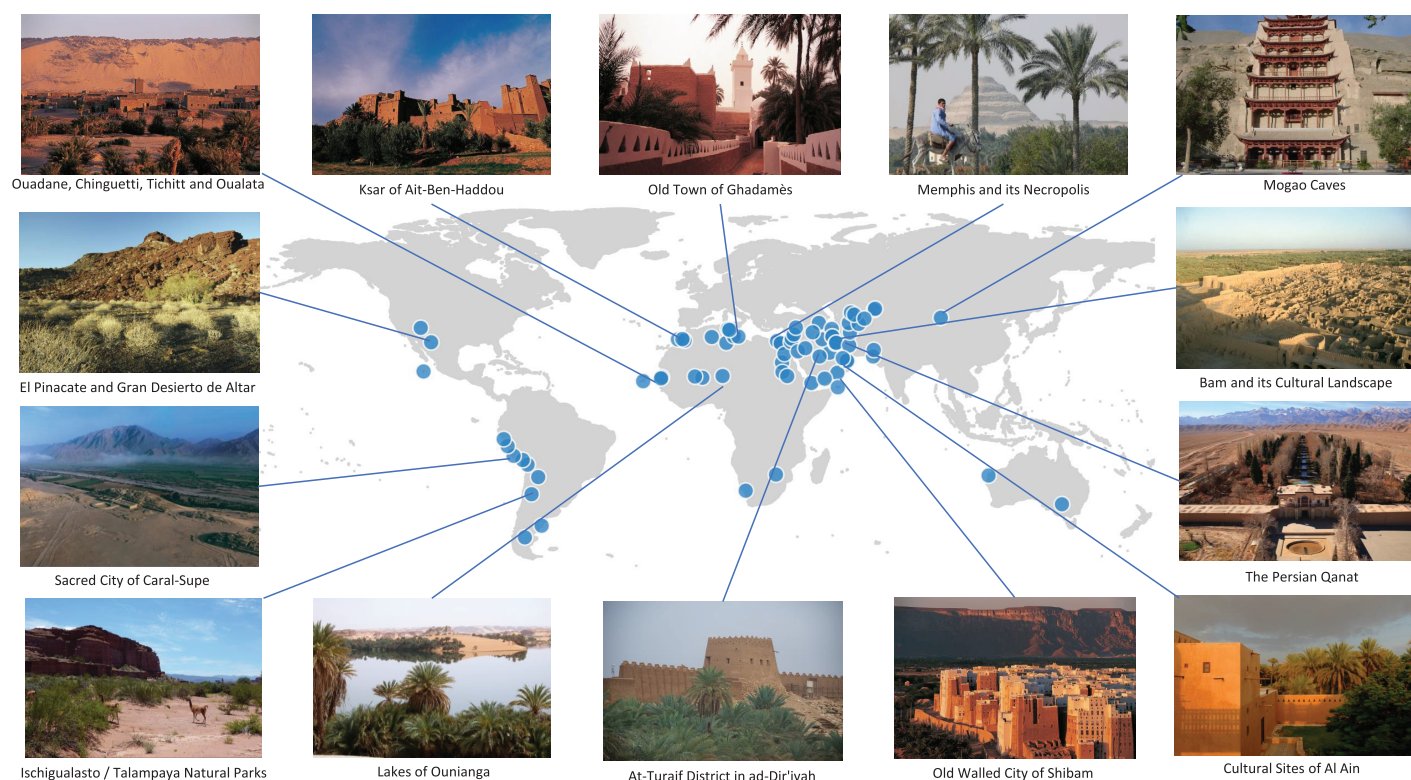
Figure 6 Location of UNESCO World Heritage sites within or adjacent to oases worldwide. The photographs of selected WHS are from UNESCO: https://whc.unesco.org/en/list. Copyright: The Persian Qanat, © S.H. Rashedi; Al Ain Palace, © ADACH; At-Turaif, © Ko Hon Chiu Vincent; Lake Yoan, © Sven Oehm; Ischigualasto, © Philipp Schinz; Bam, © Sacred Sites; Ait-Ben-Haddou, Ouadane, Chinguetti, Ghadamès and Shibam, © Editions Gelbart; Memphis and its Necropolis, © OUR PLACE The World Heritage Collection; Mogao Caves, © Neville Agnew; Sacred City of Caral-Supe, © Christopher Kleihege; El Pinacate and Gran Desierto de Altar, © Pinacate; Old Town of Ghadamès, © Editions Gelbart; Old Walled City of Shibam, © Editions Gelbart. Full-size 🖾 DOI: 10.7717/peerj.18884/fig-6

search (Table S2) and the model applied, we defined oases as: "*Azonal, highly productive areas, with permanent dense vegetation and mostly converted to agriculture, embedded in drylands and with a certain degree of isolation; they facilitate high biocultural diversity and allow biological and cultural exchange through otherwise impermeable regions.*" We are aware that this is a pragmatic definition, which may stimulate discussion and most likely requires future revision. Moreover, we need a convincing classification of oases based on origin, hydrogeomorphology, function, and state. Finally, our bibliometric search did not cover many oases in Australia or in the Americas, because other names than oases are used in these regions (*e.g.*, springs).

Bibliographic search

We identified articles covering 43 different topics, with agronomy ranking first due to major agricultural importance and expansion of oases in countries such as Tunisia (*Rodríguez-Caballero et al., 2017*), Egypt (*Elbeih, 2021*), or China (*Bai et al., 2014*). Many publications address crop varieties cultivated in oases, due to the importance oases have for specific crop species and their genetic variation (*Shachak et al., 2005*; *Buerkert et al., 2005*; *Buerkert, De Langhe & Al Khanjari, 2009*; *Davies et al., 2012*). Examples include wheat

(*Filatenko & Hammer, 2014*), maize (*Belalia et al., 2019*), alfalfa (*Loumerem et al., 2007*), apricot (*Bourguiba et al., 2013*), date palm (*Zehdi-Azouzi et al., 2015*), and pistachio (*Choulak et al., 2019*), both regionally and globally. An additional research focus was on water resources, for example on salinity in oases (*Zhao, Chang & He, 2004*; *Wang & Li, 2013*; *Yin et al., 2021*). Agronomy and hydrology control the contemporary distribution, state and future persistence of oases. Concurrently, the past conditions explain the present status and the role oases play for people and nature. In Egypt, for example, paleontology and archaeology are predominant subjects of published articles (*e.g.*, *Brookes, 1989*; *Moiisen, 1992*; *Kamal El-Din, 2003*; *El-Saadawi et al., 2014*). More recently, remote sensing technology is applied (*Luedeling & Buerkert, 2008*; *Contreras et al., 2011*; *Moat et al., 2021*; *Liu, Wang & Xin, 2022*) to study oasis expansion (*Chen et al., 2022*) and land use changes, which again may alter local environmental conditions such as precipitation (*Cai et al., 2019*).

Biodiversity has been widely explored in oases, in the past but also in recent times. Examples include studies on ants (*Taheri et al., 2021*), beetles (*Jaskuła & Rewicz, 2015*), bees (*Falcon-Brindis & León-Cortés, 2023*), ticks (*Zhao et al., 2018*), grasshoppers (*Soudani & Moussi, 2020*), birds (*Selmi & Boulinier, 2003*), and bats (*Loumassine et al., 2020*). Studies also cover the genetic variation of species such as honeybees (*Shaibi & Moritz, 2010*). However, a systematic survey of biodiversity *sensu lato* is missing at local to global scales and through time.

Mapping oases globally

This study provides a state-of-the-art delineation and quantification of oases on the global scale. Current numbers can be compared with those reported for individual countries such as China (*Liu, Wang & Xin, 2022*) or Oman (*Luedeling & Buerkert, 2008*). We mapped 198 oases for China, while *Liu, Wang & Xin (2022)* only mentioned 93 oases. Indeed, the delineation of oases remains challenging. For example, the number of oases in China has decreased during the past 20 years, probably due to the expansion and concurrent fusion of oases. We included six articles published prior to the year 2000, which may cover oases that no longer exist as individual oases. In addition, discrepancies in the nomenclature of oases may lead to an overestimation of the total number of oases within a given country. The spatial distribution of Chinese oases in our study is consistent with the recent study by *Liu, Wang & Xin (2022)*. The primary discrepancy may be attributed to the fact that certain oases, which have been the subject of only a limited number of studies (see Fig. 2), are included within the boundaries of other oases. The Qinghai region represents a significant point of controversy, with our study listing only three oases, whereas the predictions by Liu et al. result in additional oases within this region.

Luedeling & Buerkert (2008) listed a total of 2,663 different oases in Oman, while we included only 68 oases in our database. In contrast to our approach, *Luedeling & Buerkert (2008)* considered every vegetation patch as an oasis. Our prediction, with a resolution of ~250 m (the resolution used in their approach), resulted in 2,262 different vegetation patches in Oman, a number much closer to the results shown in their article.

Moat et al. (2021) calculated a total area of oases of 12,000 km^2 in Peru and 5,000 km^2 in Chile. Our calculations (Table S7) result in an area of 19,000 km^2 for Peru and 9,800 km^2 for Chile. *Moat et al. (2021)* studied arid coastal belt fog oases only, while we also included non-coastal oases (*e.g.*, oases of San Pedro de Atacama).

Some countries have zero or only a low number of oases in existing databases, although we identified oases in our predictions (*e.g.*, Afghanistan, Australia, Botswana). This reflects a lack of research in certain regions, especially in Africa (*Pimm, 2007*), or differences in the terminology applied (see above). For example, a recent initiative aimed to document the world's 'oases' defined as springs in drylands (*Fensham et al., 2023a*). That article provided a map with 14,518 coordinates of drylands springs, showing a certain level of overlap with the database presented here, although no detailed methodological information or a comprehensive list of coordinates was provided. It is evident that there are major discrepancies among the databases covering semi-arid and arid regions. While our database only contains information about oases located in arid areas and hyper-arid, the study by *Fensham et al. (2023a)* included thousands of coordinates plotted in semi-arid regions. This phenomenon is especially notable in North America, Southern Europe, and Australia. There, the 'Dryland Springs Database' contains the highest number of coordinates, in sharp contrast to the present study, in which majority of coordinates are located in arid or hyper-arid regions.

Random forest had been used before as the most suitable model for estimating vegetation cover of oases (*Wang et al., 2022*), and aridity index and NDVI have been applied in the past to classify arid lands (*Gamo, Shinoda & Maeda, 2013*). The latter methodology resulted in four different categories: Severe deserts, semi-arid regions, soil degradation areas, and areas including irrigated land and oases. Irrigated land, where vegetation is abundant despite dry conditions, are defined as NDVI$_{ymx} \geq 3.2$AI (*Gamo, Shinoda & Maeda, 2013*). This category covers 0.8% of global land surface, while our calculations yielded 0.68%, similar to the results found by *Thenkabail et al. (2009)*, indicating that our estimations are in line with previous approaches. Finally, the most comparable approach to ours to date (*Cui et al., 2024*) estimated a global area covered by oases of about 2 million km^2, which corresponds to around 1.2% of the global surface area. This prediction is almost two times higher than our prediction; primarily explained by discrepancies within Asia (see next paragraph).

ANA region: in-depth case analysis

Oases in the ANA countries cover, based on our analyses, more than 400,000 km^2. To put this number in context, global lakes cover 2,670,000 km^2 (*Messager et al., 2016*), while global urban areas cover 621,000 km^2 (*He et al., 2019*). In China the estimated total area of oases was 243,000 km^2 in 1987, which increased to 331,700 km^2 in 2017 (*Chen et al., 2022*). Other sources reported an increase from 207,812 km^2 in 2000 to 289,751 km^2 in 2020 (*Liu, Wang & Xin, 2022*). Our predictions exhibited an area of only 12,239 km^2 in China. Most oases predicted in *Liu, Wang & Xin (2022)* can be also found in our models (Fig. 3), although the total spatial extent is considerably smaller in the present study. This is most likely due to methodological differences; while we consider NDVI median values higher

than 0.2, no restriction in this parameter was used for mapping oases in China by *Liu, Wang & Xin (2022)*.

Chinese oases are characterized by the presence of deciduous tree species, such as the poplar *Populus euphratica* and the salt cedar *Tamarix chinensis* (*Li et al., 2020*), as well as the presence of crops, mostly restricted to the months April to September (*Sun et al., 2020*). The reduction of leaf material in the winter months leads to a decrease of the total NDVI values, thus resulting in a much lower spatial extent of oases compared to the methodologies used by *Liu, Wang & Xin (2022)*, *Chen et al. (2022)* and *Cui et al. (2024)*. The principal advantage of our methodology, in comparison to existing approaches, is the utilization of coordinates from a global array of locations to construct a random forest model, as opposed to focusing on a specific region or country. By using a consistent, standardized methodology across different geographical areas, we enable meaningful comparisons between regions and continents. While this approach may result in reduced modelling power for individual region, the benefits of standardization and global applicability outweigh this limitation.

The discrepancies in the number of oases, or predicted in our random forest model, may also reflect the challenge with the definition of oasis. The border of a given oasis is often difficult to determine, considering their fractal nature, from isolated and contiguous oases to archipelagos, including fluvial oases. Irrigated areas predicted by *Gamo, Shinoda & Maeda (2013)* existed in large river basins. Fringing oases along large rivers (*e.g.*, Nile River in Egypt, Punjab River in Pakistan, or Euphrates and Tigris rivers in Iraq) are not typically considered oases, while other riverine areas are widely defined as oases (*e.g.*, Draa river in Morocco, Tarim river in China). We define oases as "…*highly productive areas with permanent dense vegetation, embedded in drylands…*" which aligns with the consideration of oases along dryland rivers where vegetation remains present seasonally permanent; contrast to temporary vegetation presence in drylands, such as deciduous tree crops. It is crucial to develop and establish a consensus regarding the definition (and typology) of oases that integrates both scientific understanding and indigenous and local communities knowledge. This may facilitate the modelling of the distribution, status, trend and relevance of oases, regionally to globally. Our approach encompasses a range of definitions (Table S2) aligning with the underlying conceptual framework as well as with a detailed spatial description.

Species richness and conservation status

Oases disproportionately contribute to dryland biodiversity, with 70 % of all dryland vertebrates recorded in oases. This is a higher share than previously reported by *IUCN (2022)* for drylands (*Brito & Pleguezuelos, 2020*). At the same time, more than 10% of all reported species are threatened, illustrating a high conservation value of oases for vertebrate species and overall biodiversity. Despite their value, oases are not yet included in global conservation planning. Indeed, only 0.32% of the area is actually under protection. *Moat et al. (2021)* stated that 4% of oases are protected in Peru and Chile, compared to less than 0.5% in the present study. This difference may be explained by the types of protected areas considered. We focused on internationally listed protected areas (*i.e.*, IUCN

categories I to VI), while all types of protected areas were used for the Andean fog oases. In any case, the low level of protection makes oases one of the most sensitive and threatened regions in the world (cf. *Hoekstra et al., 2005*). Typically, steppes are considered the most threatened terrestrial habitats (*Wesche et al., 2016*), but oases may be even more endangered. The Thirty-by-thirty (30 × 30) objective aims to preserve 30% of terrestrial and marine habitats by 2030; the inclusion of oases is considered vital for the conservation of drylands including desert biodiversity (*Eckert et al., 2023*). Our research represents a pioneering contribution to the field, emphasizing the vulnerability of otherwise highly neglected ecosystems.

Human population, land use, World Heritage sites

Drylands harbor close to 40% of the total human population, but only 343 million people live in desert (arid hyper-arid) areas. Twenty years ago, oases were estimated to contain more than 150 million inhabitants (*Clouet & Dollé, 1998*; *RADDO, 2002*). Considering that the human population has grown by 25% in the last 20 years, the human population inside oases would thus be up to 190 million people. These results agree with those found in our study. We determined a total of 150 million people living inside oases in ANA countries. For arid western China, more than 95% of the total human population and 90% of the social wealth are gathered in oases, which occupy only 4% of the respective land area (*Li, Li & Wang, 2007*). This is the most up-to-date estimation of the human population currently inhabiting oases. Moreover, most people live adjacent to oases, benefiting from the resources they provide without occupying these highly valuable ecosystems.

The land cover of oases differs among countries (Fig. 5). In some countries, oases are mostly composed of natural grasses, while in others crop land and urban areas dominate. This discrepancy may explain differences in oasis terminology among countries. Oases in Inner Asia except China (*i.e.*, Russia, Kazakhstan, and Mongolia) are characterized by low human impacts and herbaceous vegetation, while oases in the Middle East are mostly managed for agriculture and therefore harbor woody vegetation (*e.g.*, date palm trees). Finally, oases in Australia exhibit a low degree of human alteration and are covered by forests. Indeed, our model underestimates oases in China, while it overestimates oases in southern Australia or southwestern North America. For Australia, this could be explained by a higher vegetation cover compared to arid areas with a similar climate. Indeed, in Australia, a long history of spatial isolation has facilitated the adaptation of many plant species to dry environments (*Maestre et al., 2021*).

Additional research is needed to improve model predictions and broaden the knowledge base of oases at the global scale. Current global predictions (*Cui et al., 2024*) provide important information on hydrological trends, which are particularly relevant in the context of climate change, and offer insights into past land-use changes. However, previous research has not investigated or mapped the biocultural diversity that oases harbor. Our research goes beyond previous contributions by not only explicitly addressing but also mapping biocultural diversity. Oases include significant cultural sites, such as 75 UNESCO World Heritage Sites (Fig. 6), which represent 6.2% of all WHS globally; although oases only cover 0.7% of land surface. They are also home to up to 70% of all

dryland vertebrates, 13% of which are classified as threatened. However, less than 0.5% of their total area is currently protected, making oases one of the least conserved ecosystems worldwide, as stated above. Overall, our findings highlight the crucial role oases play in global biocultural diversity, while underscoring the urgent need to protect these ecosystems and the unique diversity they support. To ensure transparency and replicability, we provide all data openly under FAIR (Findable, Accessible, Interoperable, Reusable) principles (Supplemental Materials), offering tools and opportunities for other scientists to build upon this line of research.

Future research

This article provides a comprehensive open-source database including an overview of research results obtained during the past decades, and reveals a global map of oases, which may facilitate interdisciplinary research on oases. There is an urgent need to map the past and present distribution of oases more accurately, characterize them, including the delineation of individual oases and to identify the underlying mechanisms that explain the multifaceted trends oases are exposed. Research questions may include: i) What is the status and the trend of oases in terms of cultural and biological diversity? ii) How fragile are (traditional) oases across geographical areas and types in terms of loss of acreage, population, and biocultural diversity? iii) What is the impact of climate change and groundwater exploitation on the environmental, ecological, and cultural status? iv) In what ways can traditional and sustainable oasis management and indigenous and local knowledge be more economically viable than current practices? v) How does a changing geopolitical context impact oases, and what role do oases play for human and animal migration? vi) To what extend can tourism be utilized to sustain oases instead of causing excessive exploitation?, and vii) can tourism improve awareness of traditional knowledge and mainstream environmental responsibility? We are convinced that the present study will stimulate research on oases and increase the awareness about the status and the futures of these fascinating albeit threatened ecosystems.

CONCLUSIONS

Oases represent vital albeit neglected ecosystems of global significance, playing crucial roles in supporting and maintaining biodiversity, ecological integrity, and having a rich cultural heritage. However, oases face escalating threats from various human activities and environmental changes, necessitating major attention and concerted conservation efforts. The conservation and management of oases must be improved by integrating ecological, socio-economic, and cultural dimensions. This requires collaborative efforts involving indigenous people and local communities, policymakers, scientists from various disciplines, and conservation practitioners. Our global analysis is considered an important step towards achieving these goals. Moreover, providing a comprehensive, open-source database of research results, covering past, present and future trends, will facilitate the study and sustainable use of oases as pivotal ecosystems for nature and people alike.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Juan Antonio Hernández-Agüero conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Mechthilde Falkenhahn performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Jessica Hetzer analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Karsten Wesche conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Christiane Zarfl conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Klement Tockner conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:
The articles reviewed, oases found, and all results are available in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.18884#supplemental-information.

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21/29

REFERENCES

Abatzoglou JT, Dobrowski SZ, Parks SA, Hegewisch KC. 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data* **5(15)**:1–12 DOI 10.1038/sdata.2017.191.

Ainiwaer M, Ding J, Kasim N. 2020. Deep learning-based rapid recognition of oasis-desert ecotone plant communities using UAV low-altitude remote-sensing data. *Environmental Earth Sciences* **79(10)**:216 DOI 10.1007/s12665-020-08965-w.

Ait-El-Mokhtar M, Fakhech A, Anli M, Ben-Laouane R, Boutasknit A, Wahbi S, Meddich A. 2020. Infectivity of the palm groves arbuscular mycorrhizal fungi under arid and semi-arid climate and its edaphic determinants towards efficient ecological restoration. *Rhizosphere* **15**:100220 DOI 10.1016/j.rhisph.2020.100220.

Bai J, Chen X, Li L, Luo G, Yu Q. 2014. Quantifying the contributions of agricultural oasis expansion, management practices and climate change to net primary production and evapotranspiration in croplands in arid northwest China. *Journal of Arid Environments* **100–101**:31–41 DOI 10.1016/j.jaridenv.2013.10.004.

Bai J, Wang N, Hu B, Feng C, Wang Y, Peng J, Shi Z. 2023. Integrating multisource information to delineate oasis farmland salinity management zones in southern Xinjiang, China. *Agricultural Water Management* **289(2)**:108559 DOI 10.1016/j.agwat.2023.108559.

Baioni E, Fiantanese G, Porta GM. 2024. Data-Driven assessment of climate change and vegetative cover dynamics in traditional oases. SSRN (preprint) DOI 10.2139/ssrn.4963954.

Belalia N, Lupini A, Djemel A, Morsli A, Mauceri A, Lotti C, Khelifi-Slaoui M, Khelifi L, Sunseri F. 2019. Analysis of genetic diversity and population structure in Saharan maize (*Zea mays* L.) populations using phenotypic traits and SSR markers. *Genetic Resources and Crop Evolution* **66(1)**:243–257 DOI 10.1007/s10722-018-0709-3.

Beresford-Jones D, Pullen AG, Whaley OQ, Moat J, Chauca G, Cadwallader L, Arce S, Orellana A, Alarcón C, Gorriti M, Maita PK, Sturt F, Dupeyron A, Huaman O, Lane KJ, French C. 2015. Re-evaluating the resource potential of lomas fog oasis environments for Preceramic hunter-gatherers under past ENSO modes on the south coast of Peru. *Quaternary Science Reviews* **129(4)**:196–215 DOI 10.1016/j.quascirev.2015.10.025.

BirdLife. 2022. BirdLife international and handbook of the birds. *Available at http://datazone.birdlife.org/species/requestdis* (accessed 7 August 2023).

Bourguiba H, Khadari B, Krichen L, Trifi-Farah N, Mamouni A, Trabelsi S, Audergon J-M. 2013. Genetic relationships between local North African apricot (*Prunus armeniaca* L.) germplasm and recently introduced varieties. *Scientia Horticulturae* **152(49)**:61–69 DOI 10.1016/j.scienta.2013.01.012.

Brito JC, Pleguezuelos JM. 2020. Desert biodiversity—world's hot spots/globally outstanding biodiverse deserts. *Encyclopedia of the World's Biomes* **2-5**:10–22 DOI 10.1016/B978-0-12-409548-9.11794-4.

Brookes IA. 1989. Early holocene basinal sediments of the dakhleh oasis region, south central Egypt. *Quaternary Research* **32(2)**:139–152 DOI 10.1016/0033-5894(89)90071-9.

Buchhorn M, Lesiv M, Tsendbazar NE, Herold M, Bertels L, Smets B. 2020. Copernicus global land cover layers—collection 2. *Remote Sensing* **12(6)**:1044 DOI 10.3390/rs12061044.

Buerkert A, De Langhe E, Al Khanjari S. 2009. Ecology and morphological traits of an ancient *Musa acuminata* cultivar from a mountain oasis of Oman. *Genetic Resources and Crop Evolution* **56(5)**:609–614 DOI 10.1007/s10722-009-9442-2.

Buerkert A, Nagieb M, Siebert S, Khan I, Al-Maskri A. 2005. Nutrient cycling and field-based partial nutrient balances in two mountain oases of Oman. *Field Crops Research* **94(2–3)**:149–164 DOI 10.1016/j.fcr.2004.12.003.

Cai P, Hamdi R, Luo G, He H, Zhang M, Termonia P, De Maeyer P. 2019. Agriculture intensification increases summer precipitation in Tianshan Mountains. *China Atmospheric Research* **227(4)**:140–146 DOI 10.1016/j.atmosres.2019.05.005.

Chen Y, Fang G, Li Z, Zhang X, Gao L, Elbeltagi A, El SH, Duan W, Mohamed O, Wassif A, Li Y, Luo P, Selmi A, Yu R, Yang J, Hu Y, Liu C, Long Y, Malik I, Fu A, Wistuba M, Yang Y, Zhu C, Gao Y. 2024. The crisis in oases: research on ecological security and sustainable development in arid regions. *Annual Review of Environment and Resources* **49**:58.

Chen BM, Wang GX, Cheng DL, Deng JM, Peng SL, An FB. 2007. Vegetation change and soil nutrient distribution along an oasis-desert transitional zone in northwestern China. *Journal of Integrative Plant Biology* **49(11)**:1537–1547 DOI 10.1111/j.1774-7909.2007.00531.x.

Chen P, Wang S, Liu Y, Wang Y, Li Z, Wang Y, Zhang H, Zhang Y. 2022. Spatio-temporal patterns of oasis dynamics in China's drylands between 1987 and 2017. *Environmental Research Letters* **17(6)**:64044 DOI 10.1088/1748-9326/ac740b.

Choulak S, Marzouk Z, Chatti K, Rhouma-Chatti S, Ouni R, Chatti N. 2019. Genetic diversity, phylogeography and population gene flow of *tunisian pistacia vera* L. *Turkish Journal of Botany* **43(6)**:737–748 DOI 10.3906/bot-1810-44.

Church TM. 1996. An underground route for the water cycle. *Nature* **380(6575)**:579–580 DOI 10.1038/380579a0.

Clouet Y, Dollé V. 1998. Aridity, oases and small production, hydraulic requirements and fragility social: an approach by spatial and socio-economic analysis. *Science and Changes Planetary/ Drought* **9**:83–94 [In French].

Contreras S, Jobbágy EG, Villagra PE, Nosetto MD, Puigdefábregas J. 2011. Remote sensing estimates of supplementary water consumption by arid ecosystems of central Argentina. *Journal of Hydrology* **397(1–2)**:10–22 DOI 10.1016/j.jhydrol.2010.11.014.

Cui B, Gui D, Liu Q, Abd-Elmabod SK, Liu Y, Lu B. 2024. Distribution and growth drivers of oases at a global scale. *Earth's Future* **12(4)**:e2023EF004086 DOI 10.1029/2023EF004086.

Davies J, Poulsen L, Schulte-Herbrüggen B, Mackinnon K, Crawhall N, Henwood WD, Dudley N, Smith J, Gudka M. 2012. *Conserving dryland biodiversity*. Nairobi, Kenya: IUCN.

de Haas H, El Harradji A. 2001. *Migration, agricultural transformations and natural resource exploitation in the oases of Morocco and Tunisia. Final Scientific Report, IMARROM Project 2001, IC18-CT97–0134 (EC, DGXII, INCO-DC)*. Amsterdam, The Netherlands: University of Amsterdam.

Eckert I, Brown A, Caron D, Riva F, Pollock LJ. 2023. 30×30 biodiversity gains rely on national coordination. *Nature Communications* **14**:7113 DOI 10.1038/s41467-023-42737-x.

El-Saadawi W, Kamal-El-Din M, Wheeler EA, Osman R, El-Faramawi M, El-Noamani Z. 2014. Early miocene woods of Egypt. *IAWA Journal* **35(1)**:35–50 DOI 10.1163/22941932-00000046.

Elbeih SF. 2021. Evaluation of agricultural expansion areas in the Egyptian deserts: A review using remote sensing and GIS. *The Egyptian Journal of Remote Sensing and Space Science* **24(3)**:889–906 DOI 10.1016/j.ejrs.2021.10.004.

Falcon-Brindis A, León-Cortés JL. 2023. The oases of Baja California Peninsula: overlooked hotspots for wild bees. *Journal of Insect Conservation* **27**:117–128 DOI 10.1007/s10841-022-00432-0.

Falcón-Brindis A, Rodríguez-Estrella R, Jiménez ML. 2019. Disentangling the coexistence strategies of mud-daubing wasp species through trophic analysis in oases of Baja California peninsula. *PLOS ONE* **14(11)**:e0225266 DOI 10.1371/journal.pone.0225266.

Faure H, Walter RC, Grant DR. 2002. The coastal oasis: ice age springs on emerged continental shelves. *Global and Planetary Change* **33(1–2)**:47–56 DOI 10.1016/S0921-8181(02)00060-7.

Fensham RJ, Adinehvand R, Babidge S, Cantonati M, Currell M, Daniele L, Elci A, Galassi DMP, de la Hera Portillo Á, Hamad S, Han D, Jawadi HA, Jotheri J, Laffineur B, Mohammad AH, Naqinezhad A, Navidtalab A, Nicoll K, Odeh T, Re V, Sanjuan B, Souza V, Stevens LE, Tekere M, Tshibalo E, Silcock J, Webb J, van Wyk B, Zamanpoore M, Villholth KG. 2023a. Fellowship of the spring: an initiative to document and protect the world's oases. *Science of the Total Environment* **887**:163936 DOI 10.1016/J.SCITOTENV.2023.163936.

Fensham RJ, Ponder WF, Souza V, Stevens LE. 2023b. Extraordinary concentrations of local endemism associated with arid-land springs. *Frontiers in Environmental Science* **11**:746 DOI 10.3389/fenvs.2023.1143378.

Filatenko A, Hammer K. 2014. Wheat landraces from Oman: a botanical analysis. *Emirates Journal of Food and Agriculture* **26(2)**:119.

Gamo M, Shinoda M, Maeda T. 2013. Classification of arid lands, including soil degradation and irrigated areas, based on vegetation and aridity indices. *International Journal of Remote Sensing* **34(19)**:6701–6722 DOI 10.1080/01431161.2013.805281.

Gebauer J, Eike AE, Ae L, Hammer K, Maher AE, Ae N, Buerkert A, Gebauer J, Luedeling E, Nagieb ÁM, Buerkert ÁA, Hammer K. 2007. Mountain oases in northern Oman: an environment for evolution and in situ conservation of plant genetic resources. *Genetic Resources and Crop Evolution* **54(3)**:465–481 DOI 10.1007/s10722-006-9205-2.

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. 2017. Google earth engine: planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* **202(3)**:18–27 DOI 10.1016/j.rse.2017.06.031.

Gossel W, Ebraheem AM, Wycisk P. 2004. A very large scale GIS-based groundwater flow model for the Nubian sandstone aquifer in Eastern Sahara (Egypt, northern Sudan and eastern Libya). *Hydrogeology Journal* **12(6)**:698–713 DOI 10.1007/s10040-004-0379-4.

Guezoul O, Chenchouni H, Sekour M, Ababsa L, Souttou K, Doumandji S. 2013. An avifaunal survey of mesic manmade ecosystems Oases in Algerian hot-hyperarid lands. *Saudi Journal of Biological Sciences* **20(1)**:37–43 DOI 10.1016/j.sjbs.2012.10.001.

Harper D. 2023. Etymology of oasis. *Available at* https://www.etymonline.com/word/oasis (accessed 7 August 2023).

He Q, Zeng C, Xie P, Tan S, Wu J. 2019. Comparison of urban growth patterns and changes between three urban agglomerations in China and three metropolises in the USA from 1995 to 2015. *Sustainable Cities and Society* **50(3)**:101649 DOI 10.1016/j.scs.2019.101649.

Hijmans RJ, Phillips S, Leathwick J, Elith J. 2021. *dismo: species distribution modeling*. R package version 1.3-3. *Available at* https://CRAN.R-project.org/package=dismo.

Hoekstra JM, Boucher TM, Ricketts TH, Roberts C. 2005. Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters* **8(1)**:23–29 DOI 10.1111/j.1461-0248.2004.00686.x.

Huang F, Ochoa CG, Chen X, Cheng Q, Zhang D. 2020. An entropy-based investigation into the impact of ecological water diversion on land cover complexity of restored oasis in arid inland river basins. *Ecological Engineering* **151(6)**:105865 DOI 10.1016/j.ecoleng.2020.105865.

IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services (summary for policy makers). In: Brondizio ES, Settele J, Díaz S, Ngo HT, eds.

PBES (2019): Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat, 1148 DOI 10.5281/zenodo.3831673.

IUCN. 2022. *The IUCN red list of threatened species.* Version 2022-2. *Available at* https://www.iucnredlist.org (Accessed August 2023).

Jaskuła R, Rewicz T. 2015. Tiger beetles (Coleoptera: Carabidae: Cicindelinae) of Tunisia: distribution, phenology, taxa list and new records. *African Entomology* **23(2)**:467–485 DOI 10.4001/003.023.0217.

Jia B, Zhang Z, Ci L, Ren Y, Pan B, Zhang Z. 2004. Oasis land-use dynamics and its influence on the oasis environment in Xinjiang, China. *Journal of Arid Environments* **56(1)**:11–26 DOI 10.1016/S0140-1963(03)00002-8.

Kamal El-Din MM. 2003. Petrified wood from the Farafra Oasis. *Egypt IAWA Journal* **24(2)**:163–172 DOI 10.1163/22941932-90000329.

Lal R. 2019. Carbon cycling in global drylands. *Current Climate Change Reports* **5(3)**:221–232 DOI 10.1007/s40641-019-00132-z.

Lei W, Changbin L, Xuhong X, Zhibin H, Wanrui W, Yuan Z, Jianmei W, Jianan L. 2020. The impact of increasing land productivity on groundwater dynamics: a case study of an oasis located at the edge of the Gobi Desert. *Carbon Balance and Management* **15**:W03437 DOI 10.1186/s13021-020-00142-7.

Li J, Feng Q, Guo Q. 2008. Fractal study of sustainable proportions of natural and artificial oases. *Environmental Geology* **55(7)**:1389–1396 DOI 10.1007/s00254-007-1089-8.

Li W, Li Z, Wang J. 2007. Evaluation of oasis ecosystem risk by reliability theory in an arid area: a case study in the Shiyang River Basin, China. *Journal of Environmental Sciences* **19(4)**:508–512 DOI 10.1016/S1001-0742(07)60085-0.

Li Y, Wang Y-G, Houghton RA, Tang L-S. 2015. Hidden carbon sink beneath desert. *Geophysical Research Letters* **42(14)**:5880–5887 DOI 10.1002/2015GL064222.

Li S, Zhang Z, Wang T, Yan C, Du H. 2020. Oasis functional stability evaluation based on multiple indicators, Northwest China. *Acta Geologica Sinica-English Edition* **94(3)**:624–636 DOI 10.1111/1755-6724.14535.

Liang Y, Liu L. 2017. An integrated ecosystem service assessment in an artificial desert oasis of northwestern China. *Journal of Land Use Science* **12(2–3)**:154–167 DOI 10.1080/1747423X.2017.1308024.

Ling H, Xu H, Fu J, Fan Z, Xu X. 2013. Suitable oasis scale in a typical continental river basin in an arid region of China: a case study of the Manas River Basin. *Quaternary International* **286(1–4)**:116–125 DOI 10.1016/j.quaint.2012.07.027.

Liu X, Shen Y. 2018. Quantification of the impacts of climate change and human agricultural activities on oasis water requirements in an arid region: a case study of the Heihe River basin China. *Earth System Dynamics* **9(1)**:211–225 DOI 10.5194/esd-9-211-2018.

Liu X, Wang Y, Xin L. 2022. China's oases have expanded by nearly 40% over the past 20 years. *Land Degradation and Development* **33(18)**:3817–3828 DOI 10.1002/ldr.4425.

Loumassine HE, Bonnot N, Allegrini B, Bendjeddou ML, Bounaceur F, Aulagnier S. 2020. How arid environments affect spatial and temporal activity of bats. *Journal of Arid Environments* **180(3)**:104206 DOI 10.1016/j.jaridenv.2020.104206.

Loumerem M, Ferchichi A, Haddad M, Rahim MAA, Hajjaji H. 2007. Collection and evaluation of lucerne (*Medicago sativa* L.) germplasm from oases of Tunisia. *Genetic Resources and Crop Evolution* **54(8)**:1645–1651 DOI 10.1007/s10722-007-9275-9.

Luedeling E, Buerkert A. 2008. Typology of oases in northern Oman based on Landsat and SRTM imagery and geological survey data. *Remote Sensing of Environment* **112(3)**:1181–1195 DOI 10.1016/j.rse.2007.08.007.

Lü S, An X, Chen Y. 2004. Simulation of oasis breeze circulation in the arid region of the Northwestern China. *Science in China, Series D: Earth Sciences* **47(S1)**:101–107 DOI 10.1360/04zd0011.

Maestre FT, Benito BM, Berdugo M, Concostrina-Zubiri L, Delgado-Baquerizo M, Eldridge DJ, Guirado E, Gross N, Kéfi S, Le Bagousse-Pinguet Y, Ochoa-Hueso R, Soliveres S. 2021. Biogeography of global drylands. *New Phytologist* **231(2)**:540–558 DOI 10.1111/nph.17395.

Maestre FT, Eldridge DJ, Soliveres S, Kéfi S, Delgado-Baquerizo M, Bowker MA, García-Palacios P, Gaitán J, Gallardo A, Lázaro R, Berdugo M. 2016. Structure and functioning of dryland ecosystems in a changing world. *Annual Review of Ecology, Evolution, and Systematics* **47**:215–237 DOI 10.1146/annurev-ecolsys-121415-032311.

Messager ML, Lehner B, Grill G, Nedeva I, Schmitt O. 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications* **7**:1–11 DOI 10.1038/ncomms13603.

Mihi A, Tarai N, Chenchouni H. 2019. Can palm date plantations and oasification be used as a proxy to fight sustainably against desertification and sand encroachment in hot drylands? *Ecological Indicators* **105**:365–375 DOI 10.1016/j.ecolind.2017.11.027.

Moat J, Orellana-Garcia A, Tovar C, Arakaki M, Arana C, Cano A, Faundez L, Gardner M, Hechenleitner P, Hepp J, Lewis G, Mamani J-M, Miyasiro M, Whaley OQ. 2021. Seeing through the clouds-Mapping desert fog oasis ecosystems using 20 years of MODIS imagery over Peru and Chile. *International Journal of Applied Earth Observations and Geoinformation* **103(1–4)**:102468 DOI 10.1016/j.jag.2021.102468.

Millennium Ecosystem Assessment ME. 2005. *Ecosystems and human well-being: synthesis.* Washington, D.C: Island Press.

Moiisen SA. 1992. Cretaceous plant microfossils from the subsurface of Kharga Oasis, Western Desert, Egypt. *Journal of African Earth Sciences* **14(4)**:567–577 DOI 10.1016/0899-5362(92)90089-U.

Pimm SL. 2007. Africa: still the dark continent. *Conservation Biology* **21(3)**:567–569 DOI 10.1111/j.1523-1739.2007.00697.x.

Powell O, Fensham R. 2016. The history and fate of the Nubian Sandstone Aquifer springs in the oasis depressions of the Western Desert, Egypt. *Hydrogeology Journal* **24(2)**:395–406 DOI 10.1007/s10040-015-1335-1.

QGIS. 2021. QGIS geographic information system. Open Source Geospatial Foundation Project. *Available at* http://qgis.org.

R Core Team. 2020. *R: a language and environment for statistical computing. Available at* https://www.R-project.org/.

RADDO. 2002. The voice of oases at the world summit for durable development in Johannesburg. *Available at* https://www.raddo.org/web/index.php//Publications/The-voice-of-oasis.

Ramsar. 2013. *Ramsar convention manual.* 6a edición. Gland (Suiza): Secretaría de la Convención de Ramsar. [In Spanish].

Reynolds JF, Smith DMS, Lambin EF, Turner BL, Mortimore M, Batterbury SPJ, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B. 2007. Global desertification: building a science for dryland development. *Science* **316(5826)**:847–851 DOI 10.1126/science.1131634.

Rodríguez-Caballero E, Cantón Y, Moussa M, Solé-Benet A. 2017. Irrigated land expansion since 1985 in Southern Tunisia. *Journal of African Earth Sciences* **129**:146–152 DOI 10.1016/j.jafrearsci.2016.12.019.

Safriel U, Adeel Z, Niemeijer D, Puigdefabregas J, White R, Lal R, Winslow M, Ziedler J, Prince S, Archer E, King C. 2005. Dryland systems. In: *Ecosystems and Human Well-Being: Current State and Trends*. Washington, DC: Island Press, 623–662.

Salih A, Hassaballa AA, Ganawa E. 2021. Mapping desertification degree and assessing its severity in Al-Ahsa Oasis, Saudi Arabia, using remote sensing-based indicators. *Arabian Journal of Geosciences* **14(3)**:192 DOI 10.1007/s12517-021-06523-7.

Santoro A. 2023. Traditional oases in Northern Africa as multifunctional agroforestry systems: a systematic literature review of the provided Ecosystem Services and of the main vulnerabilities. *Agroforestry Systems* **97(1)**:81–96 DOI 10.1007/s10457-022-00789-w.

Selmi S, Boulinier T. 2003. Breeding bird communities in southern Tunisian oases: the importance of traditional agricultural practices for bird diversity in a semi-natural system. *Biological Conservation* **110(2)**:285–294 DOI 10.1016/S0006-3207(02)00231-8.

Shachak M, Gosz JR, Pickett STA, Perevolotsky A. 2005. *Biodiversity in drylands: toward a unified framework*. Walton Street, Oxford: Oxford University Press.

Shaibi T, Moritz RFA. 2010. 10,000 years in isolation? Honeybees (*Apis mellifera*) in Saharan oases. *Conservation Genetics* **11(5)**:2085–2089 DOI 10.1007/s10592-010-0088-6.

Sorensen L. 2007. *A spatial analysis approach to the global delineation of dryland areas of relevance to the CBD programme of work on dry and subhumid lands*. Cambridge, UK: Cambridge, UNEP-WCMC.

Soudani A, Moussi A. 2020. Updated checklist and assemblages of grasshoppers (Orthoptera: Acridomorpha) associated with various habitats, including oases of Central Sahara in Algeria. *African Zoology* **55(3)**:213–223 DOI 10.1080/15627020.2020.1773310.

Sun Q, Liu T, Xu M, Han Z. 2020. The optimal porosity of shelterbelts in an oasis-desert ecotone in the Junggar Basin. *Global NEST Journal* **22**:613–618.

Taheri A, Elmahroussi M, Reyes-López JL, Bennas N, Brito JC. 2021. Ants invading deserts: non-native species in arid Moroccan oases. *Journal of Arid Environments* **184**:104122 DOI 10.1016/j.jaridenv.2020.104122.

Thenkabail PS, Biradar CM, Noojipady P, Dheeravath V, Li Y, Velpuri M, Gumma M, Gangalakunta ORP, Turral H, Cai X, Vithanage J, Schull MA, Dutta R. 2009. Global irrigated area map (GIAM), derived from remote sensing, for the end of the last millennium. *International Journal of Remote Sensing* **30(14)**:3679–3733 DOI 10.1080/01431160802698919.

Tydecks L, Hernández-Agüero JA, Böhning-Gaese K, Bremerich V, Jeschke JM, Schütt B, Zarfl C, Tockner K. 2023. Oases in the sahara desert-linking biological and cultural diversity. *PLOS One* **18**:e0290304 DOI 10.1371/journal.pone.0290304.

UNEP-WCMC & IUCN. 2023. Protected planet: the world database on protected areas (WDPA) and world database on other effective area-based conservation measures (WD-OECM). *Available at* https://www.protectedplanet.net/en (accessed 8 August 2023).

UNEP-WCMC. 2007. A spatial analysis approach to the global delineation of dryland areas of relevance to the CBD Programme of Work on Dry and Subhumid Lands. Dataset based on spatial analysis between WWF terrestrial ecoregions (WWF-US, 2004) and aridity zones (CRU/UEA; UNEPGRID, 1991). *Available at* https://resources.unep-wcmc.org/products/789fcac8959943ab9ed7a225e5316f08.

UNESCO & UNEP. 2002. *Cultural diversity and biodiversity for sustainable development UNESCO & UNEP roundtable.* Johannesburg. *Available at* https://unesdoc.unesco.org/ark:/48223/pf0000132262_eng.

Vicente-Serrano SM, Pricope NG, Toreti A, Morán-Tejeda E, Spinoni J, Ocampo-Melgar A, Archer E, Diedhiou A, Mesbahzadeh T, Ravindranath NH, Pulwarty RS, Alibakhshi S. 2024. *The global threat of drying lands: regional and global aridity trends and future projections. A report of the science-policy interface. united nations convention to combat desertification.* Bonn, Germany: UNCCD.

Wang Y, Li Y. 2013. Land exploitation resulting in soil salinization in a desert-oasis ecotone. *CATENA* **100**:50–56 DOI 10.1016/j.catena.2012.08.005.

Wang S, Wang L, Zhang M, Shi Y, Hughes CE, Crawford J, Zhou J, Qu D. 2022. Quantifying moisture recycling of a leeward oasis in arid central Asia using a Bayesian isotopic mixing model. *Journal of Hydrology* **613(6)**:128459 DOI 10.1016/j.jhydrol.2022.128459.

Ward D. 2016. *The biology of deserts.* Oxford: Oxford University Press.

Wei W, Li Z, Xie B, Zhou J, Li C. 2020. Spatio-temporal change and driving force of oasis for desert reservoir from 1988 to 2016 in northwestern China. *Polish Journal of Environmental Studies* **29(1)**:871–884 DOI 10.15244/pjoes/100368.

Wesche K, Ambarlı D, Kamp J, Török P, Treiber J, Dengler J. 2016. The Palaearctic steppe biome: a new synthesis. *Biodiversity and Conservation* **25(12)**:2197–2231 DOI 10.1007/s10531-016-1214-7.

Wolf N, Siegmund A, del Río C, Osses P, García JL. 2016. Remote sensing-based detection and spatial pattern analysis for geo-ecological niche modeling of *Tillandsia* spp. in the Atacama, Chile. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLI-B2**:251–256 DOI 10.5194/isprs-archives-XLI-B2-251-2016.

Xie Y, Bie Q, Lu H, He L. 2018. Spatio-temporal changes of oases in the Hexi Corridor over the Past 30 years. *Sustainability (Switzerland)* **10(12)**:4489 DOI 10.3390/su10124489.

Yan J, Guo J. 2019. Extraction and analysis of natural vegetation cover and soil moisture using landsat TM data in the arid oasis of Xinjiang, China. *Journal of the Indian Society of Remote Sensing* **47(2)**:213–221 DOI 10.1007/s12524-018-0922-8.

Yin X, Feng Q, Li Y, Liu W, Zhu M, Xu G, Zheng X, Sindikubwabo C. 2021. Induced soil degradation risks and plant responses by salinity and sodicity in intensive irrigated agro-ecosystems of seasonally-frozen arid regions Soil salinity Soil sodicity SOTE-WNN model Soil degradation risk Plant response Sustainable land management. *Journal of Hydrology* **603(3)**:127036 DOI 10.1016/j.jhydrol.2021.127036.

Zehdi-Azouzi S, Cherif E, Moussouni S, Gros-Balthazard M, Naqvi SA, Ludeña B, Castillo K, Chabrillange N, Bouguedoura N, Bennaceur M, Si-Dehbi F, Abdoulkader S, Daher A, Terral JF, Santoni S, Ballardini M, Mercuri A, Ben Salah M, Kadri K, Othmani A, Littardi C, Salhi-Hannachi A, Pintaud JC, Aberlenc-Bertossi F. 2015. Genetic structure of the date palm (*Phoenix dactylifera*) in the Old World reveals a strong differentiation between eastern and western populations. *Annals of Botany* **116(1)**:101–112 DOI 10.1093/aob/mcv068.

Zhang Q-B, Li Z, Liu P, Xiao S. 2012. On the vulnerability of oasis forest to changing environmental conditions: perspectives from tree rings. *Landscape Ecology* **27(3)**:343–353 DOI 10.1007/s10980-011-9685-0.

Zhao W, Chang X, He Z. 2004. Responses of distribution pattern of desert riparian forests to hydrologic process in Ejina oasis. *Earth Sciences* **47(S1)**:21–31 DOI 10.1360/04zd0003.

Zhao L, Lin XM, Li F, Li KR, He B, Zhang LY, Pan JJ, Wang QR, Gao JM, Johnson N, Yuan XF, Lv JZ, Wu SQ, Liu YH. 2018. A survey of argasid ticks and tick-associated pathogens in the

Peripheral Oases around Tarim Basin and the first record of *Argas japonicus* in Xinjiang, China. *PLOS ONE* **13(12)**:e0208615 DOI 10.1371/journal.pone.0208615.

Zomer RJ, Trabucco A. 2019a. Global aridity Index and potential evapo-transpiration (ET0) climate database v2 the global aridity index (Global-Aridity_ET0) and global reference evapo-transpiration (Global-ET0). DOI 10.57760/sciencedb.nbsdc.00086.

Zomer R, Trabucco A. 2019b. Global Aridity Index and Potential Evapotranspiration (ET0) Database: Version 3. figshare. Dataset DOI 10.6084/m9.figshare.7504448.v6.

Zu R, Gao Q, Qu J, Qiang M. 2003. Environmental changes of oases at southern margin of Tarim Basin, China. *Environmental Geology* **44(6)**:639–644 DOI 10.1007/s00254-003-0808-z.