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Short Communication

Rapid global artificial oasis expansion and consequences in arid regions over the last 20 years

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Oases are unique ecological landscapes in arid regions, characterized by a distinct geomorphology and vegetation distribution [1]. They develop under arid climate conditions, relying on snow melt, springs, and shallow groundwater [2]. Moreover, oasis development represents a significant milestone in human civilization, as they coexist alongside deserts. Oases provide various ecosystem services, such as agricultural production, biodiversity protection, climate regulation, prevention of dust storm, and improvement of living conditions for human beings [3]. However, challenges exist in maintaining the stability and sustainability of the oasis ecosystems. The regional water carrying capacity is the key factor limiting the sustainable development of oases in arid regions.

In the 21st century, agriculture expansion to meet human food demand has resulted in the conversion of large areas of virgin deserts into cultivated/arable land in arid regions [4]. As a result of human activities, artificial oases are expanding rapidly, particularly in countries such as Tunisia and China [4,5]. The vegetation growth caused by oasis expansion can help restore degraded land and combat desertification. This process effectively improves vegetation coverage and biomass, thus improving arid lands for provisioning services [3,4]. Yet, the oasis expansion process significantly alters the water cycle. For example, when deserts are transformed into artificial oases, evapotranspiration rates have been found to increase by 6–20 times [6]. Most studies on the ecohydrological consequences of oasis expansion have primarily concentrated on plot scale or *in situ* measurements in arid regions [7,8]. Previous research on the oasis expansion has mainly focused on regional or national scales [4,5,7]. However, the trends and consequences such as water availability and carbon sequestration resulting from the global-scale oasis expansion require further study.

The development of cropland is a key characteristic observed during oasis expansion, where water resources and their storage are utilized for agricultural and ecological purposes [9]. The rapid development of oases is highly dependent on the availability of water resources, making them inherently unstable. Additionally, the size of oases is influenced by the population and productivity levels, posing challenges to their management in arid regions [7]. Currently, the key problem in oasis management lies in maintaining stability and promoting sustainable development [10]. If oasis expansion is not accompanied by sustainable development and suitable management strategies, it can result in a series of eco-environmental issues such as soil desertification and alkalization, groundwater depletion, as well as vegetation degradation [11]. The fragile ecological environment of oases affects ecological security and social stability in arid regions. However, the issue of water deficit resulting from global oasis expansion and the question of whether sustainable development in arid regions has received little attention. In this study, we defined croplands in arid regions as artificial oasis areas, selecting them as our study regions. We specifically focused on man-made oases (croplands) that primarily rely on irrigation in arid regions (Aridity Index, AI < 0.2). Using comprehensive and independent datasets, we first investigated

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artificial oasis trends and the associated sustainability of oasis ecosystems in global arid regions from 2001 to 2020.

The total area of oases increased from 38.59×10^4 km^2 in 2001 to 46.67×10^4 km^2 in 2020, representing a global increase of 21% (8.08×10^4 km^2) over the past two decades (Fig. 1b). The area of oases has shown an overall increase in most countries, with Tunisia, Algeria, Oman, Yemen, Namibia, and China experiencing the greatest rates of growth. However, in Mali, Russia, Saudi Arabia, South Africa, and Peru, the area of oases has declined (Fig. S1b online). Specifically, India, Pakistan, Egypt, Iran, and China have shown a significant increase in the area of oases over the past 20 years ($P < 0.001$; Fig. S2 online). The United States and Australia have had fluctuating changes in the area of oases. It's worth noting that Saudi Arabia's area of oases had an upward trend from 2001 to 2015, but it decreased after 2016 (Fig. S2 online). In 2001, the five countries with the largest oasis areas were Pakistan (9.52×10^4 km^2), United States (4.15×10^4 km^2), China (3.71×10^4 km^2), Egypt (2.91×10^4 km^2), and India (2.48×10^4 km^2), accounting for 59.0% of the global oasis areas (Fig. S1c online). By 2020, the top five countries with the largest oasis areas were Pakistan (11.24×10^4 km^2), China (6.88×10^4 km^2), United States (4.26×10^4 km^2), India (3.69×10^4 km^2), and Egypt (3.14×10^4 km^2), accounting for 62.6% of the global oasis areas (Fig. S1d online). The countries with the most significant oasis expansion over the past 20 years were China (3.16×10^4 km^2), Pakistan (1.72×10^4 km^2), and India (1.22×10^4 km^2), contributing to 75.5% of the total increase in oasis areas.

Oases in arid regions across the globe have experienced a rapid increase of 21% over the past 20 years. Such rate at which oases are developing globally in arid regions is remarkably fast and unexpected. This growth rate exceeds the 10% increase in cropland area observed in global drylands between 2003 and 2019 [9]. To validate our findings, we compared the areas of oases in different countries with irrigation areas reported by the Food and Agriculture Organization (FAO) and the Global Runoff Data Centre's Irrigation Data Sets (GRIPCmap; Fig. S3a, b online) in arid regions. The regression slopes of 1.10 and 0.87, respectively, in these comparisons, with high coefficients of determination (0.89 and 0.96), indicate accurate identification of oases in arid regions. Thus, our identification of oasis areas can be utilized to examine the global artificial oasis trends and analyze their consequences in arid regions. Although the high resolution used for identifying oases from the MCD12Q1 product was 500 m, there is inherent uncertainty in the identification of global oasis areas. The definition of croplands used by the product (MCD12Q1) requires crops to comprise more than 60% of the total land cover. The product we utilized predominantly focused on irrigated croplands in arid regions. The rain-fed croplands, as well as lands with mosaics of crops, might not be considered in the MCD12Q1 product. Importantly, we used GMIA and GRIPCmap dataset for comparison and verification, which further supports the general trend of our oasis estimate. Our studied artificial oasis in arid regions was shown an expanding trend at a global scale in the 21st century.

In arid regions, the extent of barren or sparsely vegetated lands (less than 10% vegetated cover) was decreased from 1883×10^4 km^2 in 2001 to 1816×10^4 km^2 by 2020. Additionally, 7.85×10^4 km^2 of grasslands and 2.82×10^4 km^2 of shrublands were converted to croplands over the past 20 years. Oasis expansion has primarily occurred through the conversion of grasslands

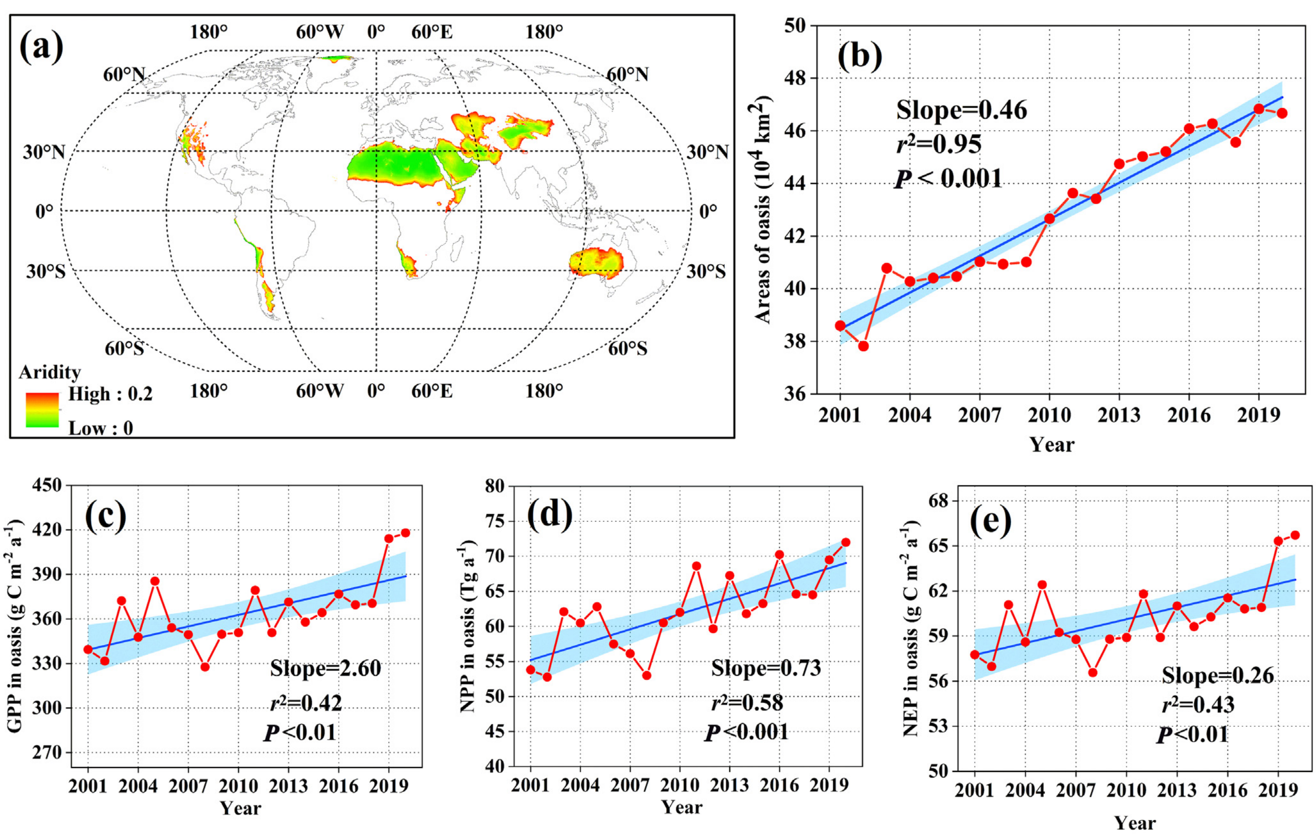

Fig. 1. Global oases expansion in arid regions and the productivity of oases ecosystem over the past 20 years. (a) Location of global arid regions with an aridity index less than 0.2; (b) Trends of global oases expansion from 2001 to 2020, with the shadows of the blue line representing the 95% confidence intervals of the regression; (c) Trends of the GPP in global oases (MODIS, MOD17A2H product, 2001–2020), with the shadows of the blue line representing the 95% confidence intervals of the regression; (d) Trends of the NPP in global oases (MODIS, MOD17A3HGF product, 2001–2020), with the shadows of the blue line representing the 95% confidence intervals of the regression; (e) Trends of the NEP in global oases, with the shadows of the blue line representing the 95% confidence intervals of the regression.

and shrublands and the cultivation of barren lands. Specially, the oasis expansion has primarily occurred in North and sub-Saharan Africa, central and west Asia at the expense of natural ecosystems, driven by the growing food demand both locally and globally [9]. As the human population and food demand have increased, there has been a noteworthy conversion of virgin desert land into arable soil. The rapid expansion of oasis areas in China, Pakistan, and India accounted for 75.5% of the overall increase. In 2020, China's oasis area was estimated at 6.88×10^4 km^2, a slight decrease from the previous estimate of 8.60×10^4 km^2, attributed to differing definitions of what constitutes an oasis [7]. This expansion has also been particularly rapid in Algeria and Tunisia, where the oasis areas have increased by two to five times since 2001. Furthermore, in some arid regions like Kazakhstan, land investors have restored the abandoned croplands for agricultural use [9]. However, in certain arid regions such as Saudi Arabia, the oasis areas have declined due to Saudi Arabia's decision to reduce wheat cultivation and production [12]. Despite some limitations and uncertainties, the present findings are adequate for the first time to better understand the global oasis expansion in arid regions.

Over the past 20 years, the annual gross primary productivity (GPP) in oases increased by 78.53 g C m^{-2} a^{-1}, corresponding to a total increase of 64.06 Tg (10^{12} grams) per year (Fig. 1c). The annual GPP in oases is comparable to GPP values of grasslands and shrublands in the United States (Fig. S4a online). The annual net primary productivity (NPP) in oases has increased, corresponding to a total increase of 18.19 Tg a^{-1} (Fig. 1d). Finally, the annual net ecosystem productivity (NEP) in oases has also increased (Fig. 1e). The NEP values in oases were comparable to NEP values of grasslands in the United States (Fig. S4b online). The expansion of oases led to an increase of 8.37 Tg in NEP in the past 20 years.

Oasis expansion facilitates meeting food demand and enhances carbon sequestration. Oasis expansion enables human beings to coexist with deserts in arid regions. The oasis areas, covering 46.67×10^4 km^2, account for a small proportion (2%) of the arid regions but support a population of 591 million in 2020. The expansion of global oases led to the increase of 8.37 Tg in NEP in arid regions over the past 20 years through enhanced crop yield and vegetation biomass. Although there is some uncertainty in analyzing oasis carbon sequestration due to the use of the same key parameters for GPP and NPP across all cropland types, the MODIS dataset remains a widely accepted tool for studying ecosystem productivity changes globally. The GPP in oases increased from 394.67 g C m^{-2} a^{-1} in 2001 to 428.38 g C m^{-2} a^{-1} in 2017, with an average of 407.50 g C m^{-2} a^{-1} according to Wang & Zhang et al. (2020) [13]. The MODIS GPP averaged 364.01 g C m^{-2} a^{-1}, which was compared with the data studied by Wang & Zhang et al. (2020) [13]. Our comparisons of the MODIS dataset with other GPP products with low values indicate that MODIS is more reliable for global oasis in arid regions. Moreover, the annual GPP and NEP in oases regions are comparable to that of grasslands in the United States [14], which further supports the modest carbon sequestration with oasis expansion in arid regions. The GPP and NPP values provided by MODIS are particularly reasonable for oasis regions, which typically have lower land productivity due to arid conditions. In contrast, croplands in the United States exhibit high GPP and NEP values, as measured by eddy covariance. This discrepancy is largely due to the favorable soil and climatic conditions in these regions [14], compared to the dry and harsher conditions found in arid regions. The MODIS GPP product applies a uniform key parameter for global croplands, without differentiating between various cropland types. This approach might introduce uncertainty in estimating oasis carbon sequestration in arid regions. To improve accuracy, it is necessary to consider using additional data sources or models for validation, such as ground-based observations or model simulations.

However, the potential water resources crisis caused by global oasis expansion and its instability were severe in arid regions. Water consumption in global oases, estimated using the Penman-Monteith-Leuning model (see Methods), and indicated a 25% increase (44 km^3) in water consumption over the past 20 years (Fig. 2a). The change in total water storage (ΔTWS) was decreased, indicating a shift

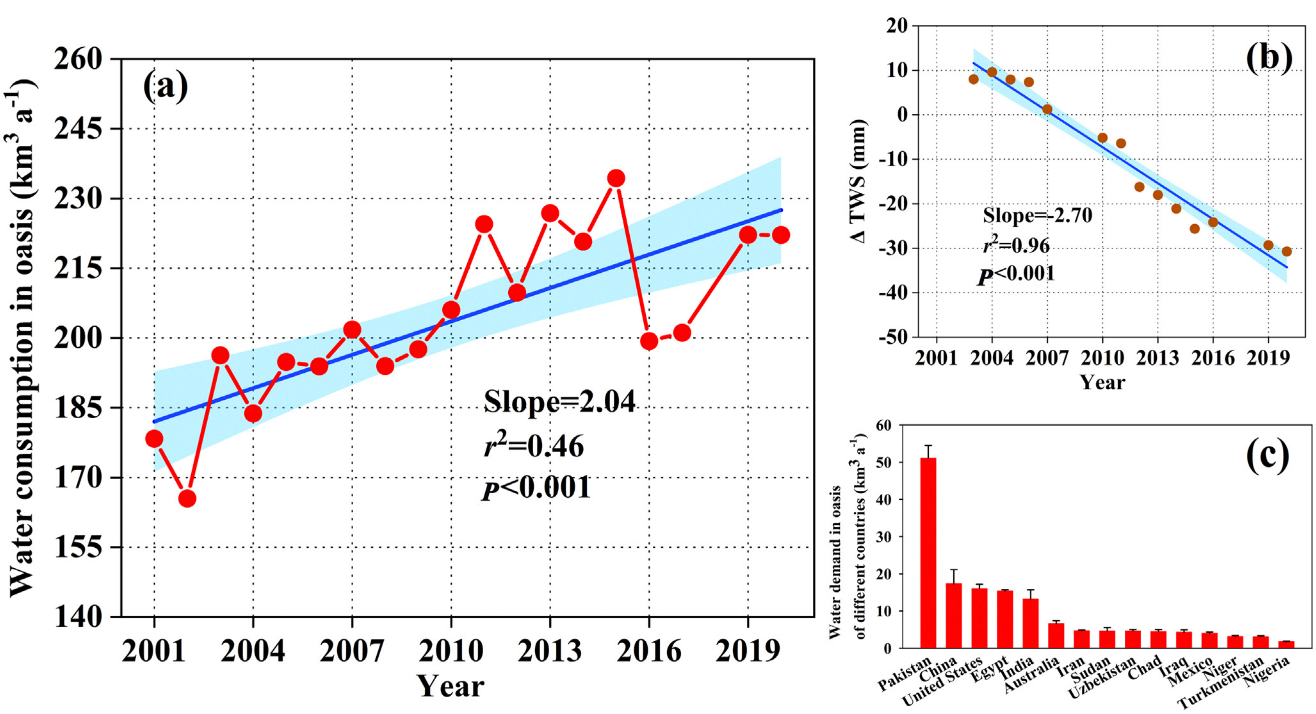

Fig. 2. Water consumption in global oases of arid regions from 2001 to 2020. (a) Trends of water consumption in global oases, with 95% confidence intervals shown as shadows of the blue regression line; (b) Trends of the terrestrial water storage anomaly (ΔTWS) from 2001 to 2020, with 95% confidence intervals shown as shadows of the blue regression line; (c) Distribution of water demand in oases in the top 15 countries, with the standard error indicated by the bar.

from groundwater recharge to groundwater depletion in arid regions. Over the past two decades, there has been a noticeable decrease in groundwater storage due to the expansion of oases (Fig. 2b). The water demand in the global oases had a significant increase over the years, rising from 142 $km^3\ a^{-1}$ in 2001 to 175 $km^3\ a^{-1}$ in 2020. Among the countries with the highest water demand in oases for agricultural purposes, Pakistan took the lead with 51.10 ± 3.43 $km^3\ a^{-1}$, followed by China with 17.35 ± 3.78 $km^3\ a^{-1}$, the United States with 16.05 ± 1.11 $km^3\ a^{-1}$, Egypt with 15.40 ± 0.29 $km^3\ a^{-1}$, and India with 13.23 ± 2.45 $km^3\ a^{-1}$ (Fig. 2c). Consequently, the total water demand in global oases for agricultural development was 163.85 $km^3\ a^{-1}$ (standard error of the mean = $\pm$ 2.92 $km^3\ a^{-1}$).

Although oasis expansion is associated with large benefits, the expansion of oases heavily relies on the excessive consumption of local water resources, resulting in groundwater depletion. Oasis expansion has resulted in an increase in water demand in arid regions. The estimated water demand for agricultural development in global oases is 163.85 $km^3\ a^{-1}$. The five countries with the highest water demand in oases are Pakistan, China, the United States, Egypt, and India, which is consistent with the distribution of oases worldwide. Furthermore, the water consumption in oases has contributed to a decrease in ΔTWS (total water storage) in arid regions since 2008 (Fig. 2b). Generally, ΔTWS decline in drylands is indicative of groundwater depletion and drought [15]. There was no significant trend observed in the annual precipitation in the arid regions during the period of 20 years. Thus, the rapid decline of ΔTWS may be primarily caused by oasis expansion. The growing agricultural water consumption and declining groundwater storage suggest that oasis expansion is unsustainable. Continually oasis expansion undoubtedly brings short-term benefits, but it could have adverse long-term consequences. Groundwater extraction for agriculture use consumes the already limited groundwater in arid regions. Groundwater extraction for irrigation increases soil evaporation, potentially leading to soil salinity and unproductive water losses. Intensive groundwater extraction in arid regions with limited recharge rates may result in unsustainable oasis agriculture. The increasing water consumption in oases, coupled with groundwater depletion, poses a significant challenge for sustaining agricultural activities in arid regions.

Many arid and semi-arid regions are inherently endorheic [16]. From April 2002 and March 2016, the global endorheic system experienced a widespread groundwater loss of about 39.94 Gt per year [16]. Surface water percolation can help replenish pumped aquifers and stabilize groundwater levels, it often comes at the expense of surface runoff [17]. In fact, water resources originating from mountains play a vital role in supporting oasis agriculture, while groundwater is another key source of water supply in these regions. Effective integrated surface and groundwater management is essential for ensuring the stability of global oasis areas. The scientific allocation and efficient utilization of water resources are vital for guiding the sustainable development of oases at an appropriate scale. Implementing proper agricultural water management can alleviate the negative environmental impacts of expanding oases on available water resources. Therefore, a threshold for the maximum oasis areas in different countries of global arid regions should be determined to align with the sustainable limits of water resources in the future research. In conclusion, oasis expansion causes the transformation of deserts into productive agricultural lands, meeting local and global food demands and bringing ecological benefits by matching available water resources. Our study is the first to examine the global expansion of oases and its environmental impact, providing a new conceptual framework to develop oases that are sustainable in terms of water resources in drylands.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Yongyong Zhang and Wenzhi Zhao conceived and directed the project. Yongyong Zhang and Lixin Wang wrote the manuscript. Xining Zhao and Wenzhi Zhao reviewed and edited the manuscript. Yongyong Zhang, Lixin Wang, Wenrong Kang, Chuan Wang, and Marwa Waseem A. Halmy analyzed the data and discussed the method.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.03.005.

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