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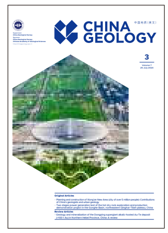

News and Highlights

Desert ecological control and ecological industrial construction: Practice and inspiration from China

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Desertification poses significant threats to the ecological security and sustainable economic and social development of countries worldwide. In China, existing desertified land primarily lies between 35°–50° N, covering arid and semi-arid regions and a total area of 1.688×10^6 km^2, which represents 17.58% of the total territorial area of the country (Fig. 1). Desertification in China causes direct economic losses exceeding RMB 6.4×10^{10} each year. Over the past 40 years, China has launched 16 ecological restoration projects and programs, including the Three-North Shelterbelt Forest Program (TSFR), the Beijing-Tianjin Sandstorm Source Control Project (BTSSCP), the Natural Forest Protection Project (NFPP), and the Returning Farmland to Forestland and Grassland Program (RFFG). These efforts have contributed significantly to the Sustainable Development Goals (SDGs) adopted by the United Nations.

1. Desertified land control in China

Monitoring data reveal that the desertified land in China has shifted from expanding at an average annual rate of 3436 km^2/yr in the 1990s to shrinking at an average annual rate of 6667 km^2/yr in recent years. The *National Desertification Prevention and Control Plan (2021–2030)* indicates that the period during 2000–2020 witnessed a 3.2% increase in vegetation coverage of deserts due to forests and grasses and a net reduction of 55.3×10^3 km^2 in the desertified land area. According to this plan, by 2030, China will achieve 124×10^3 km^2 of desertified land control and 60×10^3 km^2 of desertified land sealed off for protection, suggesting that 67% of reversible desertified land will be treated.

2. Industrial layout in deserts

China's industrial layout in deserts is classified into two categories: The ecological agriculture mode and the industrial solar photovoltaic (PV) power generation mode (Wang L et al., 2024). Both modes are significant for enhancing the ecology and increasing the economic benefits of deserts in China.

The severely and extremely severely desertified land in China covers an area of approximately 1.052×10^6 km^2, accounting for 62.3% of total desertified land in the country. Based on the regional climate and resource conditions, as well as their current status, China has determined the national ecological agriculture layout across deserts, categorizing the desertified land into five types of desertification prevention and control areas, totaling 23 (Table 1), and into four industrial layout areas (Table 2).

3. Development modes for deserts

China has formed industrial modes for the development and desertification control of deserts using various means like sand prevention and fixation, photovoltaics, agriculture, and animal husbandry.

3.1. Grass pane sand fences for sand fixation

Grass pane sand fences, also known as sand walls locally in deserts (Fig. 2a), are recognized as an environmentally friendly, low-cost, and efficient method for sand prevention and control. Specifically, materials like wheat straws, rice straws, and reeds are used, with flexibility being enhanced by spraying water. These materials are employed to build reticulate wind-break walls with a size of generally 1 m×1 m and heights ranging from 10 cm to 20 cm, which are fixed

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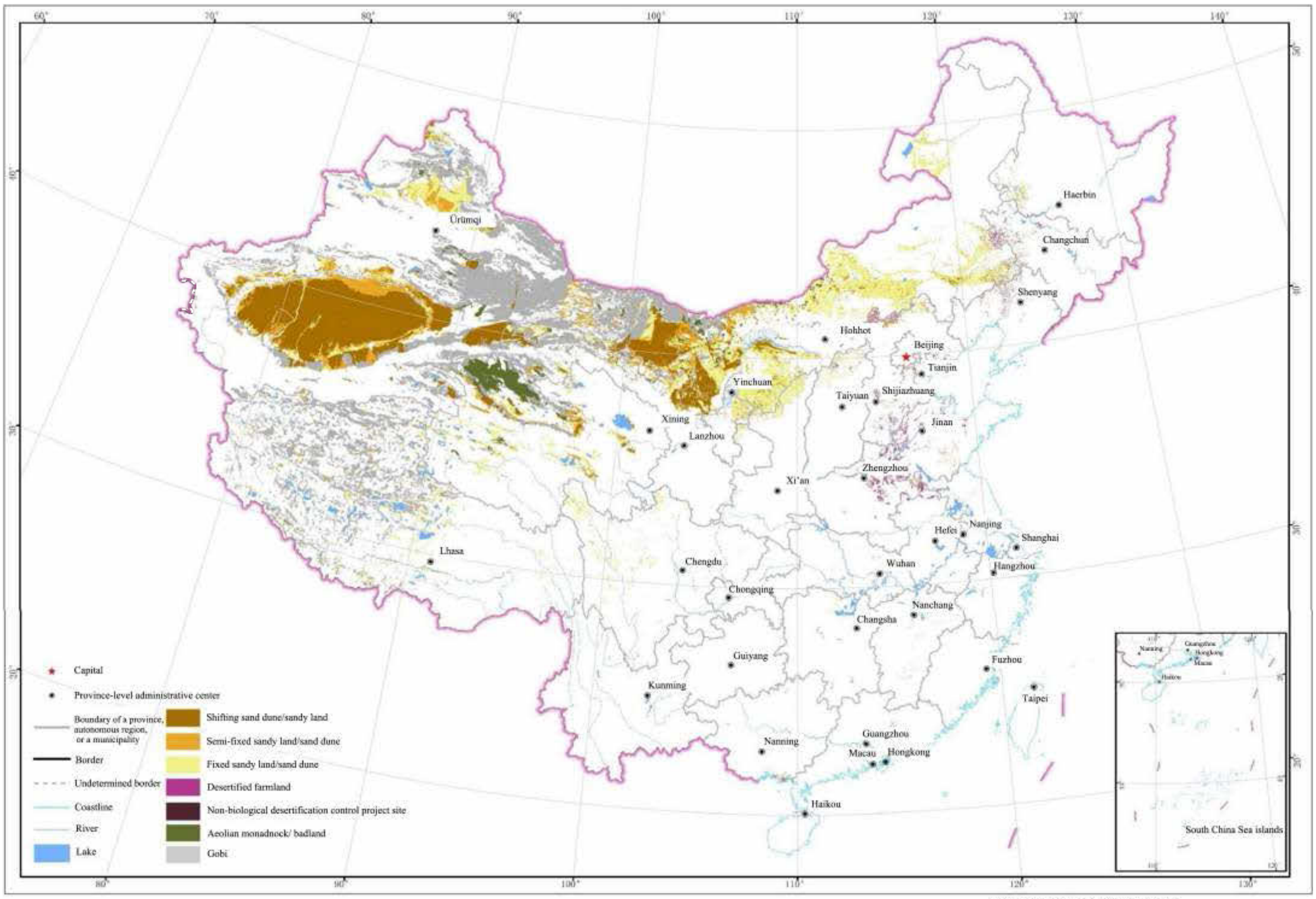

Fig. 1. Map showing the distributions of desertified land types in China (after the National Desertification Prevention and Control Plan (2021–2030)).

around shifting sand dunes with slight topographic fluctuations for wind prevention, sand fixation, and water conservation. Currently, a new lightweight grass pane machine developed by Zhongwei City of Ningxia can weave wheat straws into a brush shape and then roll them directly into the ground. This machine allows the lengths and rolling depths of grass panes to be adjusted at 750–1200 mm and 100–150 mm, respectively, effectively meeting the paving requirements. For this machine, a utility patent application (Publication No.: CN216238459U) and a national invention patent application (Publication No.: CN113550289A) have been submitted.

3.2. Afforestation and grass planting through aerial seeding for ecological restoration and desertification prevention and control

On the margin of deserts in northwest China, aerial seeding is employed to seed drought-tolerant psammophytes like *Hedysarum scoparium*, *Calligonum mongolicum*, *Artemisia sphaerocephala*, *Populus euphratica*, and *Tamarix ramosissima* during the rainy season from June to July, aiming to enhance desertification control effects (Figs. 2b, c).

For instance, in the Ulan Buh Desert within Dengkou County, Bayannur City, the Inner Mongolia Autonomous Region, aerial seeding has been utilized to seed shrub-tussock psammophytes such as *Hedysarum scoparium* and *Artemisia sieversiana*. Biological rodenticides are mixed into the seeds to prevent damage from pikas. Since 2002, aerial seeding has contributed to afforestation over an area of approximately 400×10^3 mu (a Chinese unit of land area, where one mu equals 666.7 m^2) in this desert, achieving a comprehensive vegetation cover of up to 37% in the desertification control area. A total of 52 km of sand-prevention and shoreline-protection forests, composed of shrubs and tussocks, combined with the farmland shelter belts, have been built along the Yellow River in the county. Additionally, the technique of inoculating *Cistanche deserticola* onto the roots of *Salix mongolica* has been applied in Dengkou County, with 19 enterprises currently engaged in *Cistanche deserticola* cultivation. A *Cistanche deserticola* planting base, planned to cover an area of 400×10^3 mu, will be established in this county, and it will be the largest *Cistanche deserticola* production base in China (Chen XJ et al., 2022).

On the margin of the Taklamakan Desert, a protective forest belt with a length of 2761 km has been established, with the last 285 km still under planting. Additionally, locals prepare seed balls by mixing grass seeds and the seeds of drought- and saline-alkali-tolerant trees like *Populus euphratica* and *Tamarix ramosissima* with red clay, coir, and

Table 1. Desertification prevention and control areas of desertified land in China.

Area type	Prevention and control area	Desertified land area
Arid desert and oasis	1. Ecological conservation and restoration area of the Gurbantunggut Desert and oasis 2. Ecological conservation and restoration area of the Taklamakan Desert and oasis 3. Ecological conservation and restoration area of deserts in Hexi Corridor 4. Ecological conservation and restoration area of deserts in the Alxa Plateau	$1.078×10^3$ km^2
Semi-arid desertified land	5. Comprehensive control area of mountainous-hilly desertified land in the Beijing-Tianjin-Hebei region 6. Ecological conservation and restoration area of desertified land in Hulunbuir 7. Ecological conservation and restoration area of desertified land in Horchin 8. Ecological conservation and restoration area of desertified land in Ujimqin 9. Ecological conservation and restoration area of desertified land in Hunshandak 10. Restoration area of desertified grassland in the northern piedmont of the Yinshan Mountains 11. Ecological conservation and restoration area of desertified land in Mu Us 12. Ecological conservation and restoration area of the Kubqi Desert 13. Comprehensive control area of desertified land in the Northeast China Plain	$243×10^3$ km^2
Alpine desertified land on the Tibetan Plateau	14. Ecological conservation and restoration area of deserts in the Qaidam Basin 15. Ecological conservation and restoration area of desertified land in the Gonghe Basin 16. Ecological conservation and restoration area of desertified land in the source regions of the Yangtze and Yellow rivers 17. Comprehensive control area of desertified land in the valleys of the Yarlung Zangbo, Nujiang, Lhasa, Nianchu, Yalong, and Shiquan rivers 18. Ecological conservation and restoration area of deserts in the northern Tibetan Plateau	$337×10^3$ km^2
Sub-humid and humid desertified land in the Huang-Huai-Hai Plain	19. Comprehensive control area of desertified land in the Haihe Plain 20. Comprehensive control area of desertified land along the Yellow River's original course	$20×10^3$ km^2
Humid desertified land in coastal areas and area along Yangtze River	21. Comprehensive control area of desertified land in the coastal zone 22. Comprehensive control area of desertified land in high-mountain canyons in southwest China 23. Comprehensive control area of desertified land along rivers and lakes in the and lower reaches of the Yangtze River	$9.6×10^3$ km^2

Table 2. National industrial layout areas of deserts in China.

Area type	Province or municipality	Quantity and area of counties (cities, districts, and banners) involved	Industrial layout
Forest and fruit industry promotion areas of hyper-arid desert oases	Xinjiang	64; $725.5×10^3$ km^2	PV industry, including the planting and processing of characteristic traditional Chinese herbs, such as licorice, *Cistanche deserticola*, and *Cynomorium songaricum*; the industrialization of traditional Chinese medicines in desertified land areas, and the development of national desert parks, sightseeing and leisure ecotourism areas of Populus euphratica forests; and ecological sightseeing and health tourism in deserts
Characteristic biological resource development demonstration areas of arid desertified land	Xinjiang, Inner Mongolia, Gansu	73; $351.8×10^3$ km^2	PV industry, including the industrial development of desert herbs like *Haloxylon ammodendron* inoculated with *Cistanche deserticola*, *Nitraria tangutorum* inoculated with *Cynomorium songaricum*, and licorice*, along with* green food such as *Pugionium cornutum;* the construction of artificial forage bases; and the building of ecotourism areas
Characteristic planting industry promotion areas of semi-humid and semi-arid desertified land	Beijing, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shaanxi, Ningxia	191; $243.1×10^3$ km^2	PV industry, including the construction of economic forests of shrubs such as apricots for kernels and hybrid hazelnut; the planting and processing industry of traditional Chinese herbs like licorice, *Eucommia ulmoides*, *Radix isatidis*, and *Ephedrae herba;* the standardized planting of shrubs and the deep processing of forest and grass products; the building of artificial forage bases; and ecological sightseeing and health tourism in deserts
Ecological service industry cultivation areas of alpine desertified land on plateaus	Gansu, Sichuan, Tibet, Qinghai	119; $304×10^3$ km^2	PV industry, involving the industries of characteristic food and forest fruits such as *Sophora moorcroftiana*, *Crocus sativus*, *Sedum*, *Cistanche deserticola*, and *Rubus corchorifolius* on plateaus; artificial forage bases; and ecological sightseeing and health tourism in alpine desertified land

organic matter, each weighing less than 50 g. Using these seed balls, afforestation covering $300×10^3$ mu has been achieved *via* aerial seeding in this region.

3.3. Planting of crops like characteristic medicinal plants in deserts

Agriculture has developed in deserts through water-

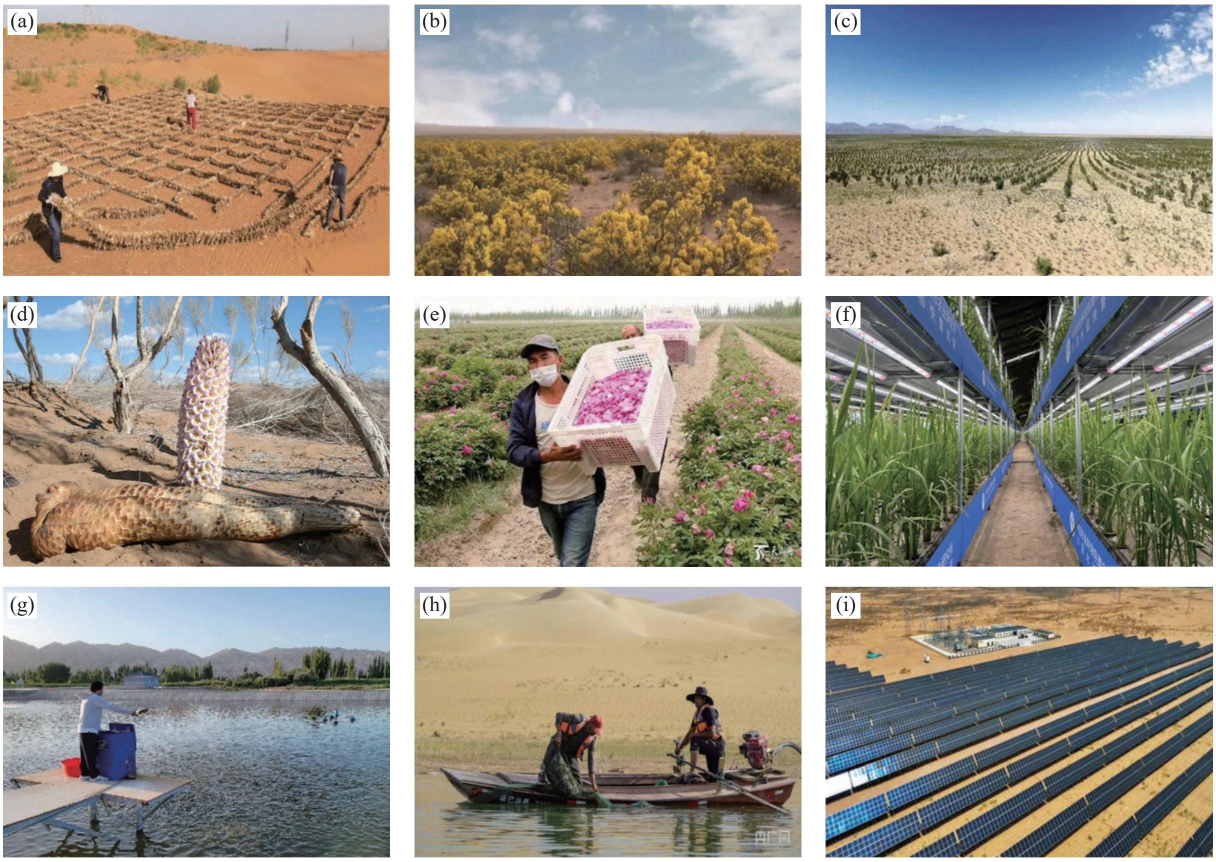

Fig. 2. Six modes of ecological management and industrialization for deserts in China (see the main body of this paper for details of a-i).

efficient irrigation and planting drought-tolerant crops (Fig. 2d). In Alxa League in Inner Mongolia Autonomous Region, which has a desertified land area of 196.9×10^3 km^2, afforestation with an area of 8.14×10^6 mu has been acquired by planting *Haloxylon ammodendron*. Of this, 1.467×10^6 mu is inoculated with *Cistanche deserticola*, whose yield represents 90% of the total of China. Besides, industrial bases of *Haloxylon ammodendron* inoculated with *Cistanche deserticola*, *Nitraria tangutorum* inoculated with *Cynomorium songaricum*, and *Hedysarum scoparium* (for seed collecting) have been established in Alxa League, contributing to an increased income of more than 30000 farmers and herdsmen (Jia LQ et al., 2023).

The sea buckthorn industrial park in Aohan Banner, Chifeng City, Inner Mongolia has an annual output of over 600 t of sea buckthorn berry, generating income exceeding RMB 4×10^6. More than 7.14×10^3 mu of sea buckthorn have been planted using the enterprise-farmer-industrial base mode, leading to an increase in per capita income of RMB 4000 for locals.

Yutian County, located on the southern margin of the Taklamakan Desert, enjoys long hours of sunshine (> 2769.5 h) and high total solar radiation (143.086 kcal/cm^2). Relying on these ecological advantages, land with an organic matter content > 15 g/kg, total nitrogen content > 0.8 g/kg, available phosphorus content > 5 mg/kg, and potassium content > 50 mg/kg in soils is selected for rose planting and processing. This enables the formation of an industrial chain of high value-added products, including essential oil-bearing natural flavors, cosmetics, essential oil-bearing drinks, flower sauce seasonings, and flower bud tea. This industry yields an economic output of RMB 180×10^6 for the entire county, increasing the income of 50000 farmer families (Fig. 2e).

3.4. Planting of crops like rice in deserts

Rice has been successfully planted in greenhouses in the deserts of Hotan, Xinjiang, enjoying the following advantages: (1) Water consumption per mu of merely 200 m^3, saving 80% of water compared to rice planted in farmland (Fig. 2f); (2) an increase in the land utilization rate by 3 to 5 times with the application of multi-layer vertical soilless culture; (3) shortened growth cycles of 60 to 70 days due to artificial light source control, representing a decrease of 50% compared to rice cultivated in traditional fields; (4) reduced planting cost of RMB 350/m^2, which is 1/3 of that of Dutch glasshouses. Currently, the rapid breeding of staple food crops like soybeans, maize, and wheat, along with other crops including oilseed rape, cotton, and alfalfa, in greenhouses is under exploration. In the future, greenhouses will be combined with new energy to further reduce costs. Hanggin Rear Banner, located on the eastern margin of the Ulan Buh Desert, hosts approximately 500×10^3 mu of well-facilitated farmland. Major crops here include wheat and maize. The wheat boasts a yield exceeding 500 kg/mu, which is 20% higher than that of local ordinary farmland, and the maize exhibits a yield of over 100 kg/mu. Additionally, 150 t of water is saved per mu using precise drip irrigation.

3.5. Mariculture in deserts

On the northwestern margin of the Taklamakan Desert, there exists 42 km^2 of natural saline-alkali land with a daily water flow of 6000 m^3. Here, the first mariculture base in Xinjiang has been established by simulating a seawater environment and using a relay mariculture mode comprised of thermostatic greenhouses for fish fry breeding, fish ponds in greenhouses, and fish ponds with alkaline water. Presently, this base hosts 16 breeding greenhouses and 1×10^3 mu of outdoor fish ponds. Eight marine products, including garoupa, abalone, tilapia, Penaeus vannamei, and lobster, are cultivated in this base, providing significant economic benefits. For instance, tilapia alone has a yield of 400×10^3 kg/yr in this base, resulting in an economic output of RMB 8×10^6 in the case of a price of RMB 22/kg (Fig. 2g).

A crab breeding base has been built at the Lop Nor Lake of the Taklamakan Desert. Soils in this area contain trace amounts of natural salts and alkali, creating favorable conditions for cultivating crab seeds. When the water temperature reaches up to 30°C, adjustments are made to the water depth and waterweed density to improve crabs' survival rate, which is reported to exceed 95%, more than 5% higher than that of the lower reaches of the Yangtze River. Crab production in the Lop Nor Lake will reach 20 t in 2024 (Fig. 2h). Moreover, species such as carp, silver carp, grass carp, catfish, and perch have been introduced to the crab breeding base, changing the ecosystem and improving regional economic vitality.

3.6. Industrial development: The mode of solar PV power generation combined with ecological management

Solar PV power generation serves as one of the most significant funding and technological channels for both industrialization in deserts and carbon emission reduction. Planting psammophytes or even fruit trees among PV panels can produce livestock feed, medicinal herbs, and fruits while fixing sands. This leads to a coordinated development between the PV industry and agriculture and animal husbandry. In the PV base in Dengkou County, an elevated height and spacing of PV arrays are applied, measuring 1.8 m and 12 m, respectively, providing enough space for the growth of crops like *Haloxylon ammodendron* and *Atriplex canescens* under PV panels. So far, 15×10^3 mu of drought-tolerant psammophytes have been planted in the base, resulting in the creation of a three-dimensional PV desertification control area (Chen XJ et al., 2022). In the PV base currently under construction in the Kubuqi Desert (Fig. 2i), various plants such as shrubs, forage grasses (like alfalfa), and medicinal herbs (like licorice) have been planted beneath PV panels. Once completed, this base is expected to achieve a greening rate of desertified land of up to 95%, allowing for the raising of 20000 sheep and 30000 chickens.

4. Implications

Presently, industries in deserts in China are continuously expanding, with those of characteristic cash crops, animal husbandry, and new energy generating an annual economic output of nearly RMB 500×10^9. Long-term experience in desertification control leads to the following suggestions: (1) Storing rainwater in inland and deserts by using the great opportunity of the global warming-induced increase in rainfall in intracontinental deserts (Fig. 3); (2) achieving a rational layout of the ecological zones, including forests and grasslands, to prevent sediment loss in the upper reaches of large rivers and reduce abrupt floods in their lower reaches for the benefit of riverside residents; (3) determining industries suitable for various deserts and adopting tailored development strategies for desertified land areas; (4) integrating desertification control, industrial development, and increased social employment into an organized system from the perspective of ecological restoration and conservation, which is essential for sustainable desertification control.

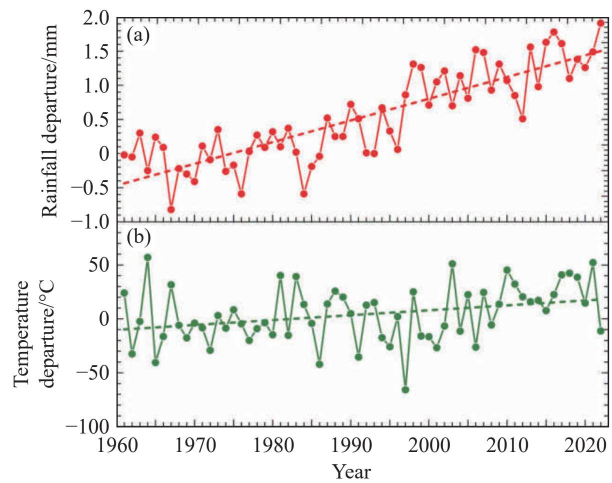

Fig. 3. Interannual variations in average temperature departure (a) and rainfall departure (b) in northwest China during 1961–2022 (Ding YH et al., 2023).

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