# Drivers and impacts of changes in China’s drylands

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## Abstract

China has 6.6 million km2 of drylands that support approximately 580 million people. These drylands are at risk of desertification. In this Review, the changes observed in China’s drylands are synthesized, with a focus on their drivers and the effects of 13 large-scale land conservation and restoration programs (such as the Shelterbelt and Grain for Green programs) that aimed to mitigate these changes. Since the implementation of the first large-scale restoration program in 1978, 45.76% of China’s drylands experienced statistically significant land improvement or vegetation greenness as identified by raw NDVI analysis. However, activities associate with the restoration and conservation projects, such as afforestation, also impose substantial water pressure. Desertification thus remains prevalent during 1980-2015, with 11.43% (especially in northeastern and northwestern drylands) experiencing statistically significant land degradation or vegetation brownness, and the drylands remain at risk of expansion due to increasing aridity, particularly in semi-arid areas. Future tradeoffs between the effects of CO2 fertilization and increased aridity on dryland vegetation cover are still poorly understood. Long-term experiments on interactions between physical‐chemical‐biological processes across spatial and temporal scales such as large-scale field surveys using standardized protocols, are needed to better manage drylands in China and globally.

## Key points

* China has 6.6 million km2 of drylands, which are at risk of expansion owing to increased aridity, potentially affecting the livelihoods of 580 million people.
* Wind, water and freeze-thaw erosion emerge as major active desertification processes; wind erosion is most serious, with rates exceeding 5000 tons km-2 yr-1.
* China has implemented large-scale land conservation and restoration programs to combat desertification, greening the drylands. However, large-scale ecological restoration projects also impose substantial pressure on these water-limited environments.
* From 1980-2015, 45.76% of China’s drylands experienced notable land improvement, while 11.43% underwent desertification.
* Plant species richness has positive effects on dryland ecosystem functioning, particularly on plant productivity and soil carbon content.
* Research is needed to examine interactions among different drivers of environmental change, particularly investigating relationships between CO2 fertilization and increased aridity.

**Table of contents summary**

Global drylands are threatened by a combination of anthropogenic climate change and human activities. Some drylands are at high risk of desertification, which can negatively impact biodiversity and ecosystem services. This Review details changes observed in the drylands of China, and the impact of large-scale restoration and conservation programs.

## [H1] Introduction

Drylands comprise about 41% of Earth's land surface, and support more than 38% of its population (> 2 billion people), approximately 90% of which are in low and middle income countries1,2. Dryland ecosystems provide a wide range of important services including water, food, energy, fiber, carbon sequestration, habitat, biodiversity and recreation3,4. However, these ecosystems are considered fragile5,6 and sensitive to desertification **[G]**7,8. Widely reported aridity increases attributed to anthropogenic climate change9,10 would cause a serious decline in ecological security **[G]**11, alongside negative ecological consequences such as soil moisture limitation and biogeochemical cycle disruption12. These changes are inconsistent with observed increases in greenness over many drylands13,14. These conflicting findings highlight the complexity of desertification processes15, and emphasize the pressing need to improve understanding of how active dryland processes will be altered in the near future16.

Drylands are regions where the aridity index **[G]** (AI) is below 0.65 (Ref17). There are four dryland subtypes defined by the AI, including hyper-arid (AI < 0.05), arid (0.05 <= AI < 0.20), semi-arid (0.20 <= AI < 0.50) and dry sub-humid (0.50 <= AI < 0. 65). Based on this definition, China has one of the largest dryland areas worldwide (6.6 million km2)18, which supports a variety of ecosystems (FIG. 1a) and 12 main deserts (FIG. 1b), which provide goods and services to 580 million people living in these areas. These drylands are characterized by low and highly variable annual precipitation and high potential evapotranspiration19,20, coarse-textured, nutrient-poor soils21, and sparse vegetation with low annual productivity22,23. The structure and functioning of dryland ecosystems in China involve complex, dynamic, interacting processes that are both spatially and temporally variable, and influenced by numerous factors that strongly affect their ability to provide ecosystem goods and services (Supplementary FIG. 1). Water is the main limiting factor and principal driver of plant biodiversity and ecosystem functioning24,25. Moreover, hydrological services (for instance, water supply) are the basis for realizing other services such as soil generation, carbon sequestration, and recreation26. However, desertification (FIG. 1c) increases the challenges related to water supply, food security, and reductions in the ecosystem carbon pool27,28.

China’s drylands are seriously threatened by desertification29, which is the outcome of coupled processes primarily resulting from climate variability exacerbated by human activities30,31. Direct economic losses caused by desertification in China’s drylands are estimated at 33.1-94.9 billion RMB annually32, constraining socio-economic progress and sustainable development21. To mitigate land degradation, 13 national initiatives aimed at dryland restoration and conservation, including China’s Great Green Wall and the Grain for Green Program, have been adopted since the late 1970s33.

In this Review, dryland ecosystem changes in China and their drivers are synthesized. In particular, China’s landscape conservation and restoration programs and their effects on dryland ecosystems are described, with the goal of advancing understanding and developing appropriate strategies to cope with continued anthropogenic climate change.

## [H1] Dryland ecosystem change

Drylands in China have mean annual precipitation of 304.0 mm, which is typically much lower than annual potential evapotranspiration (814.9 mm) (Supplementary Table 1 and Supplementary FIG. 2). Interannual rainfall variation is often high, in particular in hyper-arid (coefficient variation: 0.23) and arid (coefficient variation: 0.11) regions (Supplementary Table 1). Long-term dry periods are punctuated by rainstorms, resulting in a series of pulsed ecosystem responses34,35. In this section, the drivers and consequences of changes in drylands in China are summarized.

### [H2] Drivers of dryland changes

Wind erosion, water erosion and freeze-thaw erosion together affect 95.4% of China’s drylands (FIG. 1c). More than half (56.2%) of drylands affected by wind erosion (mostly in the northwestern and northern arid and hyper arid regions) experience at least strong erosion (>5000 tons km-2 yr-1) (Supplementary Table 2). Drylands affected by water erosion and freeze-thaw erosion are predominantly influenced by minor, mild or moderate erosion (<5000 tons km-2 yr-1) (FIG. 1c). Frost weathering is commonplace in colder high altitude climates of drylands on the Qinghai-Tibet Plateau36,37. Other processes such as salinization and alkalization can enhance desertification in drylands. Indeed, salinization affects approximately 0.17 million km2 of China’s arid and semi-arid regions where the surface soil is rich in sodium chloride and sulfate (> 0.3%)38.

Aridity and overgrazing are important drivers of widespread declines in biodiversity, ecosystem functioning and services in China’s arid and semi-arid grasslands32,39. Structural equation modelling (SEM) demonstrates the relative importance of different drivers of ecosystem functioning in drylands (Supplementary Information). Plant species richness had positive effects on both plant productivity and soil carbon content, whereas aridity negatively effects plant species richness, plant productivity, and soil carbon content (FIG. 2a). Similar results have been reported using dryland databases at regional, continental and global scales6. The effects of species richness on plant productivity and soil carbon content outweigh those of aridity: 0.55 versus -0.02 for plant productivity and 0.11 versus -0.02 for soil carbon content, respectively (FIG. 2a). The effects of plant species richness on plant productivity and soil carbon content were greater than those found in other global drylands6. These results suggest that biotic attributes can buffer negative effects of aridity, and therefore are more important drivers of China’s dryland functioning.

China’s drylands are experiencing increasing frequency and intensity of precipitation and drought40. Climate projections point to a greater risk of extreme events (for instance, rainstorms and droughts) and aridification **[G]** in arid and semi-arid regions41,42, with the semi-arid regions particularly sensitive to climate change43,44. The frequency of extreme precipitation in the northwest increased by 16.13% during 1985-2007 compared to 1961-1984 (Ref45). In parts of the north drylands, the frequency and intensity of drought extremes exceeded 10% during the past 50 years45. Decreasing precipitation and increasing temperatures enhance soil drying, leading to decreased evapotranspiration and increased sensible heat flux and temperature22, and a completely dry soil layer, desertification and dryland expansion (FIG.3)46.

### [H2] Dryland changes

Drylands in China have expanded 8.3% during 1980-2015 based on AI calculations from TerraClimate 1958-2015 datasets47. Expansion is mainly in the northeastern region and southwestern Qinghai-Tibet Plateau areas. During 1980-2015, cropland and settlement land increased by 6.5x104 km2 and 5.2x104 km2, respectively; and grassland and desert decreased by 6.3x104 km2 and 1.4x104 km2, respectively (Supplementary FIG. 3). Forest ecosystems decreased by 2.5x104 km2 during 1980-2000 and thereafter increased by 0.6x104 km2 (Supplementary FIG. 3) as a result of large-scale ecological conservation and restoration projects.

During 1980-2015, 45.76% of China’s drylands experienced statistically significant land improvement or vegetation greenness, while 11.43% (especially in northeastern and northwestern drylands) experienced statistically significant land degradation or vegetation brownness, as identified by raw NDVI analysis (FIG. 2b; Supplementary Table 3). Residual of Vegetation to Precipitation (RVP) indicator and Residual Trend analysis (RESTREND) analysis (Supplementary Information) identified similar areas with significant changes (42.66% vs 57.19%) and spatial patterns of land degradation or improvement with the raw NDVI method (FIG. 2c; Supplementary Table 3). These results indicate that NDVI trends and driving forces attributed to human activities are highly connected. 55.52% of China’s drylands had significant changes in the Sensitivity of Vegetation to Precipitation (SVP), with areas mainly distributed in the northeast showing increases, and those located in the west of China showing decreases (FIG. 2d; Supplementary Table 3). Based on combined raw NDVI, RVP and SVP results, 8.38% of China’s drylands exhibited land improvement, which is much higher than the 2.49% of areas with visible, potential and functional degradation. The spatial patterns of NDVI, RVP and SVP highlight that land improvement and degradation more closely relate to human activities than to ecosystem function (FIG. 2).

While notable expansion in the drylands of northern China48 is expected, there is conflicting evidence over whether China’s drylands will shrink under future 1.5 °C and 2.0 °C warming scenarios when using runoff and leaf area index (LAI) to delineate drylands instead of the AI14. Evidence that the dryland boundaries will overall expand under anthropogenic climate change is thus unclear and depends on the variables considered within the various models49.

## [H1] Conservation and restoration

Large-scale afforestation of degraded lands is one of the most viable solutions18 adopted to protect ecological security50,51. Since the late 1970s, China has undertaken unprecedented investment in land conservation and restoration programs, aiming at protecting forest ecosystems and biodiversity, preventing soil erosion, combating desertification and improving dryland ecosystems33,52. There have been 13 conservation and restoration programs covering a total of 3.93 million km2 of drylands (Table 1), with a cumulative investment of US$ 67.92 billion (in 2015 US$) during the period between 1978 and 2015 (FIG. 4). The 13 programs can be grouped into two categories: restoration programs, which often use afforestation, and have the goal of controlling of soil and water erosion and conserving biodiversity (P2-7, P9-10 and P12-13); and ecological programs with the goal of specifically protecting dryland ecosystems and halting desertification (P1, P8, and P11). **[Au: I wanted to make it more clear what the difference between the programs was, ideally with one word categories for each. Does this edit seem OK? Not sure if the two groups can be summarized as ‘restoration’ and ‘conservation’ programs. Actually, the second group is not just conservation programs as P1 and P8 have measures of forest plantations. That makes sense, thank you for clarifying. Are you ok to leave as ‘ecological’ then? yes]**

Four programs launched from 1978-1997 (P1–P4; FIG. 4a) failed to prevent further deterioration in many arid and semi-arid regions of China53, given a series of natural disasters including severe droughts in 1997, massive floods in 1998 and severe dust storms in the spring of 200033,54. Partly this is because the limited afforestation investments tended to focus on regions where soil moisture is available but desertification does not occur55. From 1998 onwards, China dramatically increased investment in the four existing programs (P1–P4) and launched nine new programs (P5–P13), with total annual investment increasing steadily with growth in China’s GDP (FIG. 4). Generally, investments in the three programs to combat desertification and improve dryland ecosystems (P1, P8, and P11) were lower than those of the afforestation programs (such as P5 and P13), but covered a more extensive area (FIG. 4), with programs using cheap measures such as grassland restoration and grazing exclusion33. The 13 ecological conservation and restoration programs have changed land-use patterns via forests planting, mountain closure, aerial seeding, and desert regeneration, and exerted a marked influence on dryland ecosystems32,33. In this section, the current understanding of the impacts of dryland conservation and restoration practices is synthesized.

### [H2] Forests and grasslands

Trends in forest and grassland condition coincide with implementation of ecological restoration projects that aim to enhance vegetation cover52,56. Land use and cover change showed a decrease in forested land by 2.47x104 km2 from 1980-2000, and an increase by 0.57x104 km2 from 2000-2015 (Supplementary FIG. 3). The decline in forest from 1980-2000 mainly resulted from conversion of forestland to cropland and grassland, with the value of 1.74x104 km2 and 0.92x104 km2, respectively (Supplementary FIG. 4). The increase in forest area from 2000-2015 was caused by afforestation and conversion from grassland (0.35x104 km2) and cropland (0.31x104 km2) (Supplementary FIG. 4). These results suggest that China’s drylands experienced a forest transition with a turning point in 2000. Grassland showed a continue decrease by 3.03x104 km2 from 1980 to 2015 (Supplementary FIG. 3), with reductions in all high (> 50%), moderate (20-50%) and low (5-20%) coverage grassland (Supplementary FIG. 5), related to land conversion to cropland and desert by 5.67x104 km2 and 2.17x104 km2, respectively (Supplementary FIG. 4). Both the annual and the growth-season (spring, summer and autumn) NDVI showed significant positive trends (*p* < 0.05 or *p* < 0.001, respectively) between 1998-2015 (Supplementary FIG. 6 and Supplementary Table 5).

Ecological conservation and restoration projects, such as the Grain for Green project started in 1999, provide effective measures to reduce soil erosion and land degradation in the arid and semi-arid regions of China57,58. This project is associated with significant land use and cover change through conversion of cultivated land with slopes of 25° or greater to forest, shrubland, or grassland59. As a consequence, vegetation cover on the Loess Plateau increased from 31.6% in 1999 to 59.6% in 201360. In the target areas of the Shelterbelt Development Program - Three Norths, the key aim is to increase forest cover from 5.05% in 1977 to 14.95% in 2050, by planting 35.08 million ha of forest including 26.37 million ha of tree planting, 1.10 million ha of aerial seeding, and 7.60 million ha of mountain and desert closure for vegetation regeneration; and planting 5.24 billion trees along roadsides, ditches, canals, and adjacent to houses. These large areas of trees have been planted to control sandstorms, soil erosion, and expansion of sandy and desertified land (Table 1). By the end of 2015, 37.22 million ha of forest had been planted33. However, afforestation efforts have not always been successful due to a lack of understanding about the suitability of the planted species to the local environments and their responses to climatic change61,62. High mortality ensued in many afforestation areas53. For example, the survival rate of trees in the Shelterbelt Development Program - Three Norths was only 15% during 1949-2005 (Ref53).

Vegetation greening in the semi-arid regions of China results in increases in net primary production (NPP) induced by rising CO2. However, vegetation greening by CO2 fertilization could increase evapotranspiration and decrease soil moisture63, and the continuing decrease in soil moisture indicates that the existing ecosystem is unlikely to be sustained. These changes could lead to an abrupt decline in gross primary production64. Erosion-induced land degradation is an important contributor to carbon emissions65,66, with the main mechanisms being lateral removal of soil organic carbon with eroded soil particles, and mineralization of deep soil organic carbon exposed due to erosion of the surface soil layer. Reduced soil moisture and soil degradation severely constrain primary production67 and affect the photosynthesis rate of plants that can absorb CO2 and store carbon, especially C4 plants that have high levels of photosynthesis.

Some have argued that the arid and semi-arid regions of China are not suitable for trees that require abundant water, which could make the land even drier and exacerbate desertification as well as altering catchment hydrological dynamics68,69. Large-scale plantations in the Three-North Shelterbelt Development Program have caused lower groundwater tables and greater water stress at the regional scales70. Soil desiccation in the deep soil layer caused by over-planting is widely distributed in many arid and semi-arid ecosystems of China71, showing a significant decrease by 1.5 mm during 2000-2015 compared to the period 1980-1999 over China’s drylands (FIG. 5).

### [H2] Soil and water

Large-scale revegetation projects in drylands of China have greatly increased vegetation cover (Supplementary FIG. 6), and reduced sediment loads of major rivers72. For example, the Yellow River which flows through arid and semi-arid regions was known for carrying the largest amount of sediment in the world24—1.6 billion tons annually at the point where it descends from the Loess Plateau, where approximate 91,200 km2 area has a soil erosion modulus **[G]** higher than 8,000 Mg km2 (Ref73). However, the river’s sediment load has decreased by approximately 90% over the past 60 years72. Large-scale vegetation restoration projects were mainly responsible for reducing soil erosion from the 1990s onwards72. Conversion of cropland to forest and grassland resulted in enhanced soil conservation74. The Soil and Water Conservation Program – National (P2) started in 1983 and by 2012 had been largely successful, including converting hillslope croplands into forest and grassland over > 0.67 million ha, increasing vegetation coverage by 24% on average, and reducing sediment by more than 40% in about 3800 small watersheds33. Soil conservation improved in the majority of northern drylands (Supplementary FIG. 7f).

However, ecological restoration projects introduced new threats to the water security of dryland ecosystems75,76. Soil drying caused by global warming and implementation of ecological restoration projects is widely distributed. From 1980-2015, soil moisture content showed an overall decrease by 1.5 mm over the drylands of China, especially in the northeastern regions (FIG. 6). However, such trends were not consistent in all dryland sub-types. Declines in soil moisture mainly occurred in the dry sub-humid and semi-arid regions, with the value of -7.10±5.02 mm and -0.86±0.61 mm, respectively. The arid regions showed a slight increase in soil moisture by 0.13±0.09 mm (FIG. 5). It is not possible to distinguish the individual contributions of all 13 conservation and restoration programs that have combined effects on soil moisture change at large spatial scales. However, data analysis and literature show that conservation and restoration programs contribute to greening of China’s drylands, but at the expense of increasing soil moisture depletion risks in certain regions (FIG. 6d).

Grasses (steppe and meadow) and shrubs are two major vegetation types in China’s drylands, accounting for 34.1% (21.1% for steppe and 11.9% for meadow) and 4.2% of the total dryland area, respectively (Supplementary Table 1). These two dominant vegetation types adapt their roots to utilize water efficiently and effectively. Grasses generally develop shallow-roots for utilizing water from the surface soil layer83,84, whereas shrubs usually develop tap roots to absorb water in moister soil layers at depth and release water toward the drier surface soil layers. However, many afforestation programs have used deep rooted trees in areas more suitable for shrubs and grasses, or inappropriately used shrubs where grasses are more suitable68. For example, more than 80% of the afforestation in the Three-North Shelterbelt Development Program involved monoculture planting of fast-growing but low water-use efficiency species such as *Populus tremula* L53. The overemphasis on monocultures and on tree and shrub planting resulted in ~20–40% more soil moisture consumption than the natural steppe species85, drawing the water table down at faster rates than naturel groundwater recharge, leading to soil desiccation, exacerbated land degradation and tree mortality.

Formation of a dried soil layer has negative effects on ecological and hydrological processes, preventing water exchange between the upper soil layer and ground water, reducing drought resistance of plants and limiting vegetation growth and natural succession71,86. Soil drying can also enhance dust prevalence under certain wind conditions, resulting in poor air quality and declines in crop production87. The soil drying trend is obvious especially in transitional climate regions (such as semi-arid and dry sub-humid parts) where the surface climate is highly sensitive to soil moisture46,88. In transitional regions, an increase in local surface temperature increases the energy apportioned to sensible heat and decreases soil moisture, precipitation, and temperature, leading to a drier dryland22.

Revegetation on the semi-arid Loess Plateau is reported to have already reached the threshold of soil water-carrying capacity for vegetation63. The resulting widespread dried soil layer could eventually lead to tree morality and desertification75,89. Although there are current efforts to better understand vegetation productivity thresholds63, equilibrium vegetation cover90, regional water resources development boundaries89 and soil-water carrying capacity for vegetation75,91, it is still a challenge to balance vegetation productivity and water use to sustain a healthy ecosystem.

### [H2] Desertification and dust storms

Desertification of China’s drylands has increased since the 1950s and peaked in the early 1980s, but has reversed over the past two decades27,92. According to national desertiﬁcation and sandiﬁcation **[G]** monitoring by the State Forestry Administration of China, the total desertified land decreased from 2.67 million km2 in 1999 to 2.61 million km2 in 201493. The widely observed increase in greenness and NPP (Supplementary FIG. 6 and Supplementary Table 5) also indicates a reversal of the desertification trend94,95. Long-term NDVI trends showed positive values across 71% of the drylands (mainly in the northern parts) (FIG. 2a), consistent with project areas of ecological conservation and restoration projects such as the Shelterbelt Development Program—Three North and Grain for Green Program. A comparison of land degradation or improvement conditions showed that the visible, potential and functional improvement regions over 1998-2015 were greater than those from 1982-1997 (Supplementary FIG. 8). Large-scale conservation and restoration practices and investment since 1998 have substantially improved ecosystem functions in drylands, reversing the functional degradation trend (Supplementary FIG. 8c and 8g).

Such land degradation or improvement affects local and regional climate through land surface-atmosphere interactions96,97. Vegetation restoration and degradation play an important role in changing surface attributes, surface energy fluxes, and the water balance96. Based on satellite measurements, afforestation decreased daytime land surface temperature by enhancing evapotranspiration, but led to net warming as the night-time warming offset daytime cooling98. Re-vegetation of desertified sandy land in the Horqin Desert decreased surface albedo by 15%-47% in field measurements and affected wind regimes by altering surface roughness99. In North China, vegetation greening in coupled land-atmosphere global climate models increased precipitation, which canceled out enhanced evapotranspiration and thus had weak impact on soil moisture100. Desertification of the Inner Mongolian grassland reduced rainfall and increased surface temperature101. Vegetation degradation in the arid and semi-arid regions decreased net radiation and evaporation in climate model simulations102.

Opinions differ regarding drivers of the greening. Some studies report the key explanatory factor is a reduction in wind speed (FIG. 6f) and increased spring rainfall (especially in the southeastern and most western regions of China’s drylands, FIG. 6a). However, restoration and afforestation programs in target areas (such as the Three-North Shelterbelt Development Program constructed in Horqin Desert, Mu Us Desert, and Hulunbeier Desert) could enhance the greening trend55. The main drivers of NPP changes during 2001-2010 in the Three-North Shelterbelt Program zone are climate (74%), followed by other natural and anthropogenic factors (23%); sustainability programs had a minor impact (3%)103. Climatic factors, including decreasing wind speed and reduced frequency of windy days, are also key reasons dust storm declines in northern China55, although restoration and afforestation might have contributed to trend55,104.

The pronounced greening observed in China has also been attributed to afforestation94,105. For example, satellite data during 2000-2017 showed that China accounts for 25% of global greening, and the greening has largely resulted from afforestation105. Due to the lack of long-term monitoring data it is difficult to have an overall and accurate estimation of the effects of conservation and restoration programs aiming to combating desertification (P1, P8, and P11) and their relative importance. However, widely reported lowered groundwater tables and intensified water stress resulting from large-scale plantations suggest it is uncertain that the initial target of combating desertification by conservation and restoration programs (P1, P8, and P11) could be fully achieved, especially under a changing climate and human activities in the long term.

### [H2] Carbon dynamics

Four conservation and restoration programs have the direct aim of increasing carbon sequestration in dryland ecosystems via tree plantation and protection of natural forests, including the Natural Forest Conservation Program (P5), Grain for Green Program (P6), Forest Ecosystem Compensation Fund Program (P10), and Partnership to Combat Land Degradation (P11). These large-scale conservation and restoration projects play an important role in mitigating climate change due to their positive effects on carbon sequestration106,107.

For example, the implementation of P5 increased the carbon sink by 360 million tonnes during 1998-2010. In the project areas of P11, the average annual carbon sequestration of new added forest and grassland is 14.37 and 6.05 million tonnes, respectively33. Carbon sequestration capacity over the drylands (and all four subtypes individually) showed an increase from 2000-2015. The spatial pattern indicates carbon accumulates mainly in the semi-arid Loess Plateau and northeast regions (Supplementary FIG. 7g). in a national scale investigation of terrestrial carbon stocks and changes, the annual ecosystem carbon sequestration rate during 2001-2010 was 12.4±4.6 Tg C yr-1, 5.9±1.7 Tg C yr-1, 68.4±34.6 Tg C yr-1, 24.6±7.6 Tg C yr-1, 5.2±2.9 Tg C yr-1 and 15.5±5.8 Tg C yr-1 for P1, P3, P5, P6, P9 and P13 project regions, respectively107. Their different target areas, measures and investments resulted in different contributions to the carbon sink. Implementation of the six projects contributes to 51% of the total carbon sequestration in the project regions according to a literature survey and field monitoring of soil and biomass carbon in forest, grassland, and shrubland ecosystems107. In particular, carbon sequestration in the north and northwest drylands of China accounts for 56.2% of total project-induced carbon sequestration107. In a synthesis of 135 publications (844 observations at 181 sites), land use conversion from cropland to perennial vegetation under the Grain for Green program (P6) tends to increase soil carbon stocks108. Soil organic carbon in the top 20 cm of the soil surface accrued at rates of 0.04 and 0.01 Mg ha-1 yr-1 during the 6-10 and 11-30 years after cropland conversion108. Vegetation restoration is also important in reducing total lateral carbon flux, reducing wind erosion by modifying surface roughness and reducing wind velocity109,110.

### [H2] Habitat quality

Understanding habitat quality **[G]** contributes to identification of regions where conservation and restoration practices are beneficial for natural systems and threatened species, and supports comparison of spatial patterns of biodiversity over a landscape. Habitat quality can be assessed using the InVEST Habitat Quality model, which here was produced by assessing the sensitivities of each land use/cover type to threat factors including cropland, roads, urban areas and rivers111.Habitat quality showed a slight decrease (-0.78%) in the drylands of China during 2000-2015, mainly in the semi-arid and dry sub-humid regions, with reductions of -2.44% and -2.18%, respectively. However, habitat quality in hyper-arid and arid regions increased by 7.97% and 2.69%, respectively. The spatial pattern showed that regions with improved habitat quality were mainly concentrated in the northwest. Habitat quality decreased significantly in the eastern and central part of China’s drylands, showing a deteriorating trend from west to east (Supplementary FIG. 7h). The change is mainly associated with conservation and restoration programs that aim to increase the number and extent of nature reserves. P7 (Wildlife Conservation and Nature Reserve Program) and P5 (Natural Forest Conservation Program) have generally increased natural biodiversity112,113, expanding the number of nature reserves, restoration, protection and improvement of wildlife habitat quality33. However, afforestation in certain areas has negative effects on local biodiversity due to the widespread use of non-native, fast-growing and single-species trees114, instead of using native and diverse species to support the natural ecosystem115.

## [H1] Future of restoration

China leads in large-scale land conservation and restoration programs33,60 to combat desertification105,116. From 1978 to 2015, the 13 conservation and restoration programs covered more than half (59.6%) of the total dryland area in China, and the annual restoration investment has continued to increase from 2016 to 2020(FIG. 4). Due to the implementation of these conservation and restoration programs, China’s drylands have experienced significant increases in greening (Supplementary FIG. 6), and substantial increases in water yield, soil conservation, carbon sequestration, and habitat quality, in particularly in hyper-arid and arid regions (Supplementary FIG. 7). Generally, the 13 dryland conservation and restoration programs have achieved considerable overall success with benefits for ecology, society and human wellbeing33,54.

However, restoration initiatives have also imposed substantial pressures (for instance, soil desiccation) (FIG. 6) on the water-limited dryland ecosystems. Cost-effective and scientifically-informed dryland restoration strategies require careful evaluation of local environmental conditions, long-term monitoring and technology usage117. Soil moisture recovery is complex and affected by land use, plant characteristics, inter-annual rainfall and soil texture71. Several measures have been proposed to prevent soil desiccation and contribute to soil moisture recovery, including use of appropriate local or indigenous species instead of those that require large amounts of water, and regulation of vegetation density using thinning60,118. Continuous long-term measurements of soil moisture content before and after vegetation restoration are needed to evaluate the effects of these measures. In addition, coupled climate/land-use models should incorporate numerical modeling of water transport within the soil-plant-atmosphere continuum, to better understand the effects of large-scale afforestation and climate feedbacks in the drylands of China75.

Among the 13 major dryland conservation and restoration programs in China, 10 have been or will be end in the near future of 2023 (Table 1). However, 3 programs are planned to continue until 2050 or beyond, including the P1 (1978-2050), P4 (1989–indefinite), and P7 (2001–2050). P1 has promoted massive forest planting that will continue until 2050 (Table 1). However, unintended consequences such as lowered groundwater tables and intensified water stress have occurred in this large-scale plantation program. For its 3rd stage (2021-2050), shrubs are more suitable than trees and should be the priority option for afforestation119 in the water-limited arid and semi-arid regions. As P4 continues, soil erosion is expected to decrease, and water and soil conservation capacity will be enhanced in the upper and middle reaches of the Yangtze River. However, because P4 includes areas where many people still live in poverty, further implementation of this project should balance ecological and social benefits, improving both the local environment and farmers' incomes116.

The area and investment for wildlife conservation and nature reserve protection increased rapidly from 2001 to 2015 as part of P7 (FIG.4), and is planned to expand in China’s drylands until 2050 (Table 1). Construction and protection of nature reserves thus far has improved habitat quality for rare and endangered wild biota, such as the panda and the Tibetan antelope33,120. Nature reserves are mostly located in remote and poor regions where local residents typically participate in tourism or temporarily migrate to large cities to make a living, which helps to enhance the ability of nature reserves to improve habitat quality120. Local economic development needs to be balanced with natural habitat restoration and protection of biodiversity protection, through improved funding and scientific research and monitoring121, in order to promote development in a more sustainable way116.

Forest restoration is an effective method for carbon sequestration and climate change mitigation122. Globally, terrestrial ecosystems have the potential to support an estimated additional 0.9 billion hectares of forest, representing an increase of more than 25% in tree coverage, and an extra 205 gigatonnes of carbon sequestration at maturity122. However, the potential for global forest restoration might be overestimated, especially in drylands with substantial environmental constraints123. In particular, widely applied bioenergy plantations using fast growing species require substantial irrigation water, ranging between ~400 and ~3000 km3 yr−1 globally, imposing further pressure on already stressed freshwater systems124.

Restoration practices in China’s drylands show that many tree planting programs have low tree survival rates53. *Populus tremula* L tree accounts for almost half of China's reforestation54, leading to increased water shortages in the water-limited dryland environments53,76. Insights from China’s programs have wider implications in global drylands116. In Australia, where drylands account for 91.08% of total area18, tree establishment and growth is restricted by soil moisture, salinity and sodicity125. In African drylands, water constraints, infertile soils, grazing and wildfires can only support patchy shrub-grass environments126. In badland areas with severe soil degradation in Mediterranean environments and the Americas, prospects for recovery of pre-degradation forest cover are also limited127.Therefore, it is paramount to select the right plants and appropriate management practices in restoration programs. Shrubs or grasses tend to be more suitable where drought is frequent. Dryland afforestation activities should have a moderate plant density: too low a density leads to soil erosion and ecosystem deterioration, while too high can also affect biodiversity, sustainability of the ecological programs and the associated ecological benefits.

As learned from the Chinese restoration programs, vegetation recovery rates strongly depend on available soil moisture128. The effects of forest restoration also depend on future climate change. Afforestation where water resources are scarce, such as the Loess Plateau, has reached the upper water resource limit under current climatic conditions63. Human activities including groundwater exploitation or drought caused by climate change could substantially reduce the carbon sequestration capacity of these forests up to 36% in the worst case63,129. Overall, afforestation is just one of many means to tackle with climate change. It is also important to consider vegetation and biophysical feedbacks to climate (for instance, temperature and precipitation) in order to fully assess the impacts of large-scale afforestation programs in China’s drylands54,100. It is essential for future restoration programs to be reasonably planned, well monitored and fully assessed, to prevent and further desertification in degraded drylands and to protect non-degraded drylands, in order to efficiently and effectively manage dryland ecosystems and achieve multiple Sustainable Development Goals.

## [H1] Summary and future perspectives

Biotic and abiotic interactions through space and time are vital in determining vegetation dynamics and shaping ecosystem responses in China’s drylands. Wind erosion, water erosion, freeze-thaw erosion, salinization and alkalization are key processes of desertification in China’s drylands that undermine the delivery of ecosystem goods and services. Widespread greening and land improvement indicate a decline in desertification trends, even though visible, potential and functional degradation are identified in certain regions. Anticipated rises in aridity will negatively affect ecosystem structure and functioning in the drylands of China, even if there is no clear evidence that dryland boundaries will expand overall under climate change (based on using runoff and LAI to define drylands). Large-scale ecological conservation and restoration projects enhance greening and ecosystem services in China’s drylands, but also impose considerable water stress. It is important to have a complete assessment of plant water consumption and local water availability to understand the sustainability of drylands restoration. Moreover, the effectiveness of the conservation and restoration projects should be comprehensively evaluated over multiple time frames and socio-economic aspects.

Ecosystem processes including the coupling of ecological and hydrological processes, and their interactions with desertification processes, are fundamental in driving ecosystem structure and functioning in the drylands of China. Both long-term experimental monitoring and improved process understanding are urgently required to enable better prediction of dryland ecosystem functioning. Research priorities involve using multiple techniques to conduct long-term field monitoring of water, soil, atmosphere and biological elements, energy and carbon fluxes, ecohydrological processes and key desertification processes and their interactions in major dryland ecosystems.

Future research could benefit from combining multi-scale, high-quality data sets observed within the national networks such as Chinese Ecosystem Research Network, Chinese Terrestrial Ecosystem Flux Observation and Research Network and China Desert Ecosystem Research Network130,131. However, it is difficult to extrapolate data obtained from plot scale or research stations to regional scale. Large-scale field surveys using standardized protocols (for instance, BIOCOM+, BIODESERT global survey) provide an important approach to compile and compare results from different sites12,64, and have been successfully applied to examine the effects of climate change (such as aridity) and grazing intensity on multiple ecosystem structural and functional variables132. The obtained extensive field in-situ monitoring database, together with moderate- to coarse-resolution remotely-sensed imagery at the regional scale23, are beneficial for understanding key processes and could usefully be supplemented with further networks and datasets to improve coverage133.

Soil inorganic carbon pools account for a large proportion of terrestrial carbon stocks in the drylands of China. However, little is known about the size and long-term evolution of these stocks, due to the complex interactions and exchanges between atmosphere, vegetation, soil organic matter, and different forms of soil inorganic carbon. Long-term *in situ* measurement using both conventional accurate but expensive techniques such as wet oxidation and combustion methods, and new faster and cheaper techniques such as near-infrared spectroscopy and laser-induced breakdown spectroscopy134, would be feasible options to obtain data to support the large-scale evaluation of soil inorganic carbon stocks in China’s drylands. This information would enable more accurate carbon accounting in these areas, as the dryland inorganic carbon pool accounts for 97% of global inorganic carbon stocks and 29.5% of global total carbon stocks135.

It remains a challenge to incorporate some key processes into process-based models, and to use long-term and high-quality field data for model calibration and validation. For example, interactions among soil hydrological processes and nutrient cycles are vital in changing plant productivity, structure and functioning of ecosystems in drylands75,136. Therefore, it is necessary to build coupled models that include relevant physical, chemical and biological processes and take a systems approach. An extensive database developed using multiple techniques (such as big data, machine learning, artificial intelligence137,138) is essential to understand the mechanisms of coupling interactions between soil water and nutrients, and to couple soil hydrological models and biogeochemical models. In addition, both ecohydrological and desertification processes are the outcome of coupled processes which primarily result from biotic – abiotic interactions, and are strongly influenced by human activities (for instance, grazing, fencing)27,54. Future modelling work could benefit from integrating ecological and socio-economic systems in order to better understand system interactions24,133.

Different climatic change drivers affect vegetation in different ways. Rising atmospheric CO2 enhances water-use efficiency and plant growth139, while increased aridity negatively affects water availability and plant productivity6,64. However, it is still not known whether the positive effects of CO2 fertilization can buffer the negative effects of increased aridity. To better understand dryland responses to ongoing climate change, more research is needed to reveal the feedbacks among key properties of dryland ecosystem structure and functioning and environmental change drivers. At the ecosystem level, relationships between plant functional traits, species richness, functional diversity, and dryland ecosystem multifunctionality remain unclear. More attention should be given to the responses of these variables to grazing, burning, nutrient addition and their interactions, alongside the use of controlled experiments to examine the mechanisms of plant characteristics and ecosystem processes (for instance, ecohydrological processes). At the regional scale, field sampling and surveying of soil properties (for instance, moisture, stability of soil aggregates, SOC, soil nitrogen content), plant characteristics (for instance, functional traits, species diversity and functional diversity), and land management practices (for instance, grazing, nitrogen addition, burning) is needed, along aridity gradient transects in different land use systems (such as forest, shrubland and grassland). More detailed information is available from large-scale field surveys using standardized protocols such as BIOCOM+ and BIODESERT global survey132,140.

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## Author contributions

C.L., B.F., S.W. and L.S. formulated the review and identified the themes to be covered. C.L. drafted the figures and wrote the first draft of the manuscript. Y.W. Z.L., Y.L. and W.Z conducted data analysis of land degradation in China’s drylands. B.F., S.W. and L.S. reviewed and edited the manuscript before submission. All authors made substantial contributions to the discussion of content.

## Competing interests

The authors declare no competing interests.

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## Display items

**Table 1.** Details of the 13 major dryland conservation and restoration programs in China (adapted from Bryan, et al. 33).

| Program name (number) | Time frame | Geography (priority areas) | Aim and objectives |
| --- | --- | --- | --- |
| Shelterbelt Development Program—Three North (P1) | 1978–2050 | 13 provinces (CN-XJ, QH, GS, NX, SN, SX, NM, HE, BJ, TJ, LN, JL, and 70HL70); key construction zones in areas with serious soil erosion and sandstorms. | Halt desertification in the Northwest, North, and Northeast China via forest plantations, mountain closure and desert regeneration. |
| Soil and Water Conservation Program—National (P2) | 1983–2017 | 12 provinces (CN-BJ, HE, SX, NM, LN, AH, SD, HA, SC, SN, GS, and NX); priority areas with severe soil erosion such as Northwestern Loess Plateau, Northern mountainous, Northeastern black soil, and Southern rocky mountain regions. | Reduce soil erosion, and improve livelihoods, farmer incomes, agricultural production, and the environment, through treating a small watershed as a management unit and combining prevention, protection, and restoration via scientific, engineering, and cultivation measures. |
| Shelterbelt Development Program—Five Regions (P3) | 1987–2020 | 5 shelterbelts (including the Yangtze River and Pearl River Shelterbelts, the Taihang Mountain and Plain Greenings); focusing on the construction of shelterbelts, water and soil conservation, forests, and grain-producing counties. | Slow ecological and environmental deterioration via tree planting, mountain closure, and aerial seeding. |
| Soil and Water Conservation Program—Yangtze (P4) | 1989–indefinite | Upper and middle reaches of the Yangtze River, including 5 provinces (CN-YN, SC, GS, SN, HA) | Control soil erosion, improve the environment, and enhance regional economic and social development. |
| Natural Forest Conservation Program (P5) | 1998–2020 | 13 provinces (CN-NM, HL, JL, SC, YN, XZ, SX, SN, GS, NX, QH, HA, and XJ) | Protect natural forests, control deforestation, and reforest and regenerate existing forests via mountain closure, aerial seeding and artificial planting. |
| Grain for Green Program (P6) | 1999–2020 | Implemented in all dryland provinces, including CN-BJ, TJ, HE, NM, SX, SN, GS, NX, QH, XJ, and XZ. | Alleviate soil erosion, mitigate flooding, conserve biodiversity, and increase rural household income by increasing forest and grassland cover on cropped hillslopes and converting cropland, barren hills and wasteland to forestland. |
| Wildlife Conservation and Nature Protection Program (P7) | 2001–2050 | Covers the whole of China and includes the following key dryland regions: plateau and desert areas in CN-NM and XJ; Loess Plateau region in the North China Plain; mountain and plain areas in the northeast of China; alpine areas in the Tibetan Plateau. | Protect key wild animal and plant species141, and natural ecosystems by expanding the number of nature reserves and enhancing the protection of wildlife and its habitat. |
| Sandification Control Program—Beijing/Tianjin (P8) | 2001–2022 | 6 provinces, (CN-BJ, TJ, HE, SX, NM and SN) | Reduce the risk of sandstorms, improve the ecological environment in Beijing, Tianjin and the surrounding areas via conversion of cropland to forestland, afforestation, grassland management, water conservation, and establishing basic governance of desertified lands. |
| Fast-growing and High-yielding Timber Program (P9) | 2001–2015 | The middle and lower reaches of the Yellow River region, and Northeast Inner Mongolia region. | Remedy the decline in timber supply without impacting natural forests via the establishment of fast-growing and high-yielding timber plantations. |
| Forest Ecosystem Compensation Fund (P10) | 2001–2016 | National non-commercial forest regions including the important rivers, national nature reserves, wetlands and reservoirs of importance, forest within 10 km of the national border, areas at risk of desertification or serious soil erosion, and state-owned forest reservations. | Conserve natural forests, maintain ecological balance and protect species via restoration, protection, and management of non-commercial forest ecosystems. |
| Partnership to Combat Land Degradation (P11) | 2003–2023 | 6 provinces (CN-GS, NM, NX, QH, SN, and XJ) | Improve management of land and water resources, reduce poverty, protect biodiversity, and combat climate change in western China by bringing agencies together to work synergistically. |
| Rocky Desertification Treatment Program (P12) | 2008–2020 | County -level focus in dryland provinces, including CN-YN and SC. | Curb the expansion of desertification in rocky environments, improve the ecological environment, and promote national unity and social harmony via constructing vegetation, transformation of sloping farmland, water conservation and relocation. |
| Grassland Ecological Protection Programe (P13) | 2011–2020 | 8 northwest provinces (CN-NM, GS, NX, XJ, XZ, QH, SC and YN), and parts of CN-HE, SX, LN, JL, and HL. | Mitigate grassland degradation by increasing grassland vegetation coverage and biomass yield in grazing prohibition areas. Promote the development of pastoral areas and herdsmen incomes. |

Notes: ISO 3166 — Codes for the representation of names of countries and their subdivisions were used for the provinces, special administrative regions, and autonomous regions as specified in the table. The ISO 3166 code and full names: CN-AH: Anhui Sheng, BJ: Beijing Shi, GS: Gansu Sheng, HA: Henan Sheng, HE: Hebei Sheng, HL: Heilongjiang Sheng, JL: Jilin Sheng, LN: Liaoning Sheng, NM: Nei Mongol Zizhiqu, NX: Ningxia Huizu Zizhiqu, QH: Qinghai Sheng, SC: Sichuan Sheng, SD: Shandong Sheng, SN: Shaanxi Sheng, SX: Shanxi Sheng, TJ: Tianjin Shi, XJ: Xinjiang Uygur Zizhiqu, XZ: Xizang Zizhiqu, YN: Yunnan Sheng.

**FIG. 1. Distribution and characteristics of China’s drylands.** a| Distribution of terrestrial ecosystems in drylands of China as of 2015. b| Dryland NDVI and location of deserts. c| The three key processes that cause desertification in the drylands of China, with the main local driver shown. Data is derived from the mean value of 1995, 2005 and 2010 data sets provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). Generally, desertification is caused by wind erosion and aeolian processes; water erosion and alluvial processes; freezing and thawing processes on cold plateaus. The inset graph shows the areas of the drylands and sub-types affected by wind erosion, water erosion and freeze-thaw erosion. The details for different categories of the erosion magnitudes are given in the Supplemental Table 2.

**FIG. 2.** **Dryland ecosystem change in China.**

**a|** The relative importance of aridity, grazing intensity, and plant species richness on China’s dryland functioning including soil carbon (C) and plant productivity (after Ref6). Standardized path coefficients are provided. The blue and red lines indicate positive and negative effects, respectively. The gray line shows a non-significant path. The right hand side bar diagrams show the standardized total effects of aridity, grazing intensity, and plant species richness on soil carbon content and plant productivity. Soil carbon content and plant productivity have the unit of 1, based on standardized path coefficients. **b|** The spatial pattern of land degradation or land improvement based on raw NDVI (yr-1). **c|** Residual trend of vegetation to precipitation (yr-1). **d|** The trend of the sensitivity of vegetation to precipitation (mm-1 yr-1). Green colors indicate land improvement (I) and brown colors show land degradation (D). Grey areas have non‐significant changes (NS). Both land improvement and land degradation are grouped into four categories: I1- I4 indicate land improvement (I1, *p* <= 0.001; I2, 0.001 < *p* <= 0.01; I3, 0.01 < *p* <= 0.05; I4, 0.05 < *p* <= 0.1); D1- D4 indicate land degradation (D1, *p* <= 0.001; D2, 0.001 < *p* <= 0.01; D3, 0.01 < *p* <= 0.05; D4, 0.05 < *p* <= 0.1). See Supplementary Table 3 for proportions of each category please. **e|** The spatial pattern of degradation or improvement types identified based on the three indicators and their combinations (Supplementary Table 4). Only the four significant degradation or improvement types are displayed. Type A: *visible + potential + functional* improvement (8.38%); Type D: *functional degradation* (8.51%); Type E: *visible + potential degradation* (1.51%); Type H: *visible + potential + functional degradation* (2.49%).

**FIG. 3. Feedbacks in dryland ecosystems.** Climate change, population growth and associated human activities (for instance, afforestation, deforestation, cropland and settlement expansion, and overgrazing by livestock) and their interactions are key drivers of desertification and land degradation142. There are positive feedbacks among global warming, land degradation, dryland expansion and carbon emissions from soils. Accelerated soil erosion caused by deforestation and overgrazing results in degradation of soil physical, chemical, and biological properties143. The regions around deserts and barren land are particularly exposed to high desertification risk144. Conversely, afforestation increases soil infiltration capacity145, soil C, N and P stocks, microbial biomass and α- and β- diversity of soil bacteria146. Hotter, drier conditions and extreme rainstorms are expected to further intensify147,148, and are predicted to cause dryland expansion, desiccation and degradation129,149. The expansion of drylands in China during the last sixty years48 is expected to intensify in future as population growth and associated rising water and food demands continue49, and global climate changes proceed22, particularly for the semi-arid ecosystems which are recognized as the most sensitive and vulnerable to climate change among the four dryland subtypes48.

**FIG. 4. The 13 major dryland conservation and restoration programs in China**. a| Timeline of 13 major dryland conservation and restoration programs in China from 1978 to 2015Bryan, et al. 33). P5 (the Natural Forest Conservation Program) and P6 (the Grain for Green Program) are two of the biggest programs offering payments for ecosystem services in China and worldwide in terms of scale, payment and duration54. **b|** Combined cumulative investment and area of the 13 ecological conservation and restoration projects conducted in the drylands of China. **c|** The annual investment by program, with the programs indicated along the right hand side. The values for P7 and P12 are too small to be seen. **d|** Annual area targeted by each program including both conservation and restored project areas. The values for P7 are too small to be seen. P13 is not included in the figure as it just has a value of 214.7 Mha in 2011. Data derived from Bryan, et al. 33 and adjusted to the investment and area values of China’s drylands.

**FIG. 5. Dryland ecosystem shifts, water fluxes, and ecosystem services.** **a|** Shifts between dryland ecosystem types during 2000-2015 in China. The numbers along the each of the circle indicate area, which has the unit of 104 km2. Data is derived from the Resource and Environmental Data Cloud Platform. **b|** Changes in major water cycle fluxes in China’s drylands and four sub-types from 1980 to 2015. Data is derived from TerraClimate 1958-2015 datasets47. c| Time series of water yield (WY), soil conservation (SC), carbon sequestration (CS), and habitat quality (HQ) from 2000 to 2015. Data is derived from ecosystem services evaluation datasets by Xu, et al. 111.

**FIG. 6.** **Spatial variations in climatic and hydrological change.** **a**| Annual total precipitation change from 1980-2015. **b|** As in a, but for potential evapotranspiration change. **c|** Runoff change. **d|** As in a, but for soil moisture change. **e|** As in a, but for water storage change. **f|** As in a, but for wind velocity change. **[Au: Please add a summary sentence here The climatic and hydrological variables showed great spatial differences over the drylands of China, showing an overall decrease in soil moisture, especially in the northeastern regions.]** Data is derived from TerraClimate 1958-2015 datasets47.

**Glossary terms**

desertification: a type of land degradation in drylands induced by climatic variations and human activities

ecological security: the capability of an ecosystem to maintain its stability under external stress

aridity index: the mean annual precipitation divided by potential evapotranspiration

aridification: a long-term process that drives increasing dryness

sandification: an environmental change whereby an environment becomes sandy

soil erosion modulus: an indicator to describe soil erosion rate per km2 per year.

habitat quality: an indicator which approximates the biodiversity of a landscape through estimating the extent of habit, vegetation types and their degradation states