

Review

Research Progress on Structure, Pattern, Process Coupling Mechanisms in Desert Ecosystems of Arid China

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Abstract

Nearly two-fifths of the global land surface consists of arid-land ecosystems. Their impact on changes in terrestrial carbon sinks is uneven, and their function is difficult to estimate due to water limitation. This structured narrative review integrates the coupling of structure, pattern, and process of desert ecosystems in China's arid regions. OpenAlex and Crossref were searched to identify candidate publications, supplemented by citation links, with the time span mainly covering January 2018 to July 2026, and earlier foundational research establishing relevant theoretical concepts was retained. 39 peer-reviewed publications were selected and coded. After comprehensive consideration, six recurring themes are summarized, including hierarchical organization. There is relatively strong evidence for the functional role of biological soil crusts, but there are many uncertainties regarding the transferability of idealized models. The problems that need to be addressed first involve causal relationships across scales. Solving such problems is necessary for evaluating restoration and carbon neutrality strategies, which cannot focus only on the extent of greening.

Keywords: desert ecosystem, structure-pattern-process coupling, biological soil crusts, ecohydrology, carbon-water trade-off

Introduction

About 40% of the global land belongs to arid regions, and such regions are extremely sensitive to climate change [1-3]. Their ecological significance is disproportionate to their sparse vegetation, and semi-arid ecosystems have an impact on trends in terrestrial carbon sinks [4-5]. China has many kinds of ecological zones, including desert-related landforms [6]. These

ecosystems perform functions such as stabilizing soil and their ecological functions cannot be inferred simply from vegetation cover, because the functions and resilience of the ecosystem are determined by many factors [7-9].

Existing research has advanced along four largely parallel lines. First, studies of soil microorganisms and biological soil crusts [10-12], shrub fertile islands [13-14], and restoration effects on crust-microbial communities [15, 16] have clarified how small-scale biological structures regulate surface stability, nutrient cycling, and resource concentration. Second, reaction-diffusion theory has linked banded and spotted

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vegetation to scale-dependent feedbacks [17, 18], while field observations have examined threshold behavior [8-9] and the reliability of possible early-warning signals [19, 20]. Third, ecohydrological studies have shown that precipitation pulses and antecedent soil moisture [5, 21, 22], groundwater depth [23], and ecological water conveyance [24, 25] govern vegetation persistence and carbon exchange. Fourth, research on large-scale greening and shelterbelts [26-28], warming and shrub encroachment [29, 30], grazing [31], photovoltaic microclimate [32], restoration water limits [33], and broader photovoltaic ecological responses [34-36] has revealed both ecological benefits and water, land, and biodiversity trade-offs. Together, these bodies of work provide essential mechanisms, but they are rarely synthesized within one cross-scale framework for the contrasting desert systems of China.

Accordingly, a central task in dryland ecology is to explain how structure, pattern, and process interact across scales rather than to describe each component separately [3, 6]. Here, “structure” denotes the organization of biotic and abiotic components, from microorganisms, viruses, and biological soil crusts

to individual plants, shrub patches, dunes, oases, and landscape mosaics. “Pattern” refers to the spatial arrangement, including vegetation patches, belts, gaps and the mosaic state of shrubs and grasslands; “process” refers to the hydrological, ecological, and biogeochemical dynamics that connect various components, including infiltration, runoff, evapotranspiration, nutrient cycling, carbon exchange, erosion, groundwater uptake and response to disturbances. Remote sensing, unmanned aerial vehicles, lidar, in situ soil-moisture and groundwater observations, and ecosystem models now permit these dimensions to be examined together, although their spatial and temporal resolutions remain difficult to reconcile [5, 9, 22]. Fig. 1 summarizes this conceptual framework.

There are three deficiencies in the existing literature that motivated this review. Many studies only focus on a single organizational level or process, making it difficult to establish the causal pathway from microbial organization to patch configuration and landscape-scale function [3, 6, 16]; the classic vegetation pattern model focuses on the plant-water feedback driven by rainfall, while Chinese deserts are also affected by disturbances

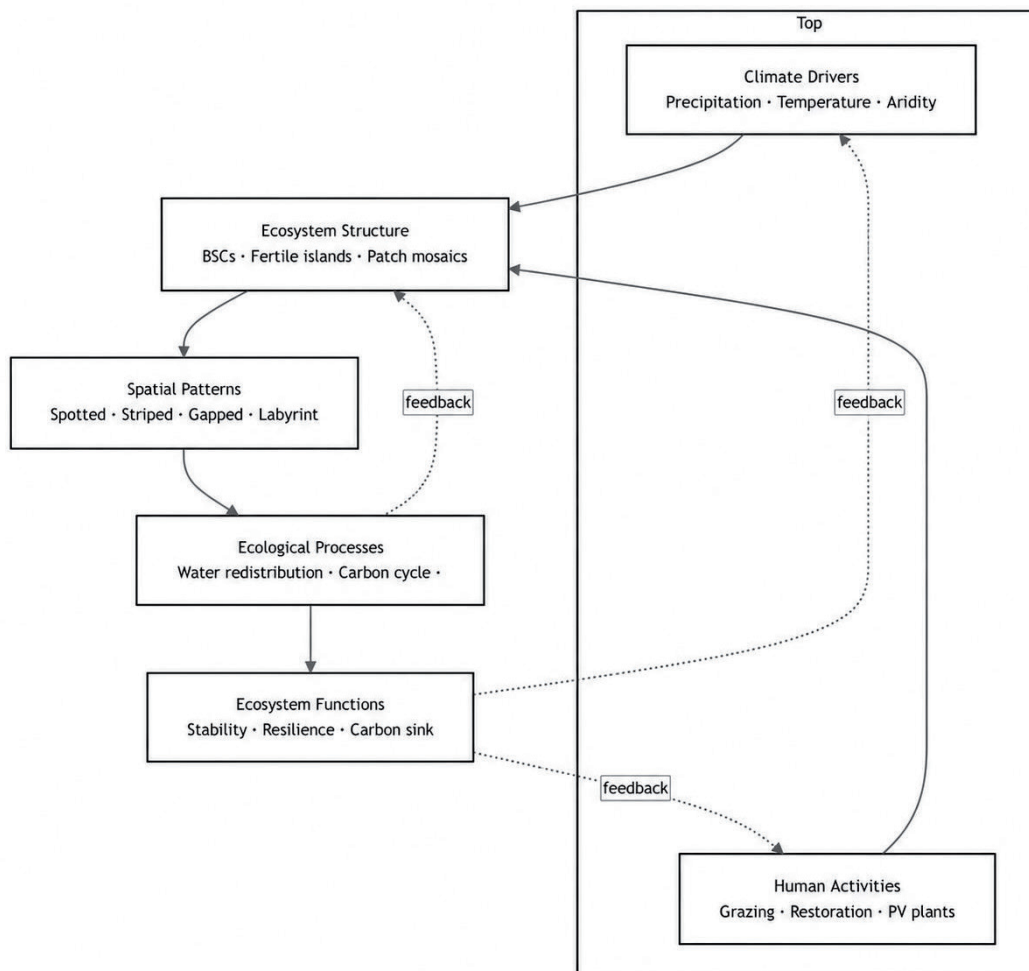


Fig. 1. Conceptual framework of structure-pattern-process coupling in desert ecosystems, integrating biological soil crusts, shrubs, microbial communities, soil-moisture conditions, vegetation patterns, carbon cycling, and cross-scale feedback mechanisms.

such as strong wind erosion [6, 20, 23]; restoration and carbon neutrality assessments emphasize greening or carbon sequestration, but do not simultaneously assess life-cycle effects such as water-resource carrying capacity [28, 33, 36]. These gaps involve mechanistic prediction and the transfer of evidence within desert areas.

This review explores the structural composition and feedback mechanisms of microbiological structures, patches, and landscape-scale ecological functions, distinguishes ecosystem resilience or environmental degradation reflected in spatial vegetation patterns from errors arising from model assumptions, considers the regulation of the carbon-water trade-off by precipitation and other factors, clarifies the progress in observation and modeling of ecological impacts of relevant development in desert areas, and, by integrating scattered evidence, identifies limitations and clarifies priorities that can be tested in future research and management.

Materials and Methods

Review Design and Scope

This study adopts a structured narrative review approach because the evidence covers various study types, such as field experiments and observational studies. The review focuses on how biological and abiotic structures in the arid desert ecosystems of China generate spatial patterns and regulate related processes. The main geographical scope covers the desert areas of China. Evidence from other arid regions is retained only when it can provide direct mechanistic relevance to the interpretation of Chinese systems.

Literature Search and Screening

Candidate publications were identified in OpenAlex and Crossref, and backward and forward citation tracking was conducted for recent reviews and highly relevant studies, following the approaches described in [3, 6, 23]. The main search covered publications from January 1, 2018, to July 31, 2026, and was last updated on August 11, 2026. Earlier studies were also considered when they introduced foundational dryland concepts or models. Geographically related terms (such as “China”), ecosystem-related terms (such as “desert ecosystem”), and mechanism- or driving-factor-related terms (such as “structure-pattern-process”) were searched and combined. Boolean combinations were adjusted according to the source, and candidate records were identified by exact title or DOI.

The screening process was divided into three steps: removing duplicate titles or DOIs, evaluating titles and abstracts, and conducting a full-text eligibility review. Publications that met the criteria were required to be peer-reviewed, relate to arid or semi-arid terrestrial

ecosystems, provide evidence related to at least one aspect such as ecosystem structure, and constitute empirical research. Non-peer-reviewed commentaries and other ineligible publications were excluded. The final number of included publications was 39: 29 publications from 2019 to 2025 and 10 earlier foundational or background publications.

Data Extraction and Thematic Synthesis

Each publication included in the structured evidence matrix was coded for elements such as authors and year. The coded evidence was classified into six thematic categories, including hierarchical ecological structure.

The synthesis was divided into three steps: summarizing the findings within each theme and identifying recurring mechanisms and existing differences; comparing evidence at micro- and other levels to determine whether the conclusions changed according to scale or desert type; and evaluating the consistency of the conclusions. Table 1 presents the scale codes for functional partitioning; Table 2 compares pattern model assumptions and field constraints; Table 3 shows the status of different ecosystems in terms of water sources. Figs 1 and 2 present a synthesis of the related concepts. A combined effect size was not calculated because the differences among the results were too large to permit a reliable meta-analysis.

Quality Control and Limitations of the Review

Priority was given to studies with clear sampling or model descriptions, clearly defined comparison groups or baselines, multiple locations or long-term observations, and conclusions supported by the evidence. DOI metadata were verified and compared with publisher records, and multiple publications were cross-checked to verify key statements. However, inter-reviewer consistency could not be assessed because only one author conducted the screening and coding. English-language and DOI-indexed literature may not be representative of Chinese-language and grey literature, and the narrative design does not comprehensively include all relevant content. These limitations require the use of cautious language and a distinction between well-supported conclusions and key points requiring further research.

Results and Discussion

The evidence matrix yielded six recurring categories, described in the following sections. The functions of biological soil crusts and the dependence of riparian vegetation on groundwater show the strongest convergence of evidence. Evidence for vegetation patterns as early-warning indicators is conditional because the conclusions depend on factors such as model assumptions. Therefore, the following sections

present the key interpretations and limiting conditions identified during coding.

Hierarchical Structures and Cross-Scale Ecological Functions

Desert ecosystems have different hierarchical divisions, and processes at each level can affect the limiting conditions of the next level. At the micro level, for example, microbial communities play a role in nutrient transformation. Many microorganisms form biological soil crusts, which can contribute carbon and nitrogen [10, 12, 16]. Meta-analysis has shown that biological soil crusts have a positive effect on soil organic carbon, and this positive impact varies with factors such as nitrogen availability [12]. Rising temperatures may cause crust organisms to decline before the cover of vascular plants decreases, so the state of the crust may show signs of functional decline earlier than green vegetation [10, 11, 16].

At the plant and patch level, shrubs intercept dead branches and leaves under the canopy to form “fertile islands”, and microbial biomass within the patches is higher than in adjacent bare gaps. In the transition zone between desert and oasis and in semi-fixed dune areas, fertile patches are key factors in creating landscape heterogeneity. Research on *Caragana korshinskii* bush sand dunes shows that the fertile island effect differs among developmental stages and promotes microbial nutrient cycling as development progresses [13, 14]. These findings indicate that desert restoration should not only focus on the survival rate of shrubs but also consider whether shrubs can rebuild nutrient islands under the canopy and restore soil-microorganism-plant feedback [14]. Table 1 summarizes the structural composition and ecological functions across scales.

Fixing drifting sand through afforestation can enhance the stability of the surface, and its effects on biological soil crusts and microbial communities vary with different environments. Carrying out different afforestation measures in alpine sandy lands leads

to changes in crust characteristics and microbial composition, showing that restoration actions not only change vegetation cover but also change the biological foundation of soil functions [15]. Mechanical stability will promote different combinations of surface roughness. The structure-related assessment needs to consider vascular plants and lichen and moss cover rather than being based only on NDVI or the survival rate of woody plants [3, 15, 16].

Vegetation Spatial Patterns: Theory, Evidence and Model Limitations

The close connection among structure, pattern, and process in drylands is clearly demonstrated by self-organized vegetation patterns. The classic model explains patterns such as bands through scale-dependent feedback. Short-distance interactions promote soil and water conservation around plants and seedling establishment, while long-distance competition depletes soil moisture in surrounding bare areas. The Klausmeier model formalizes the interaction between vegetation and water on slopes. Subsequent studies show that self-organized patchiness may occur before catastrophic transitions in ecosystems [17, 18]. Relevant explorations of arid ecosystems in the Mediterranean region show that the spatial distribution pattern of vegetation can act as an early warning sign of desertification [19].

Recently, the general model-based interpretation has been refined and qualified. The drought threshold may be associated with sudden nonlinear declines in variables such as plant cover [7-9]. The spatial pattern contains information about feedback strength, but it is not a universally reliable indicator of collapse. Under certain conditions, the formation of adaptive patterns can delay or provide opportunities to avoid critical transitions [20]. The direct application of the idealized rainfall-vegetation model to the Chinese desert is limited. The Mu Us Sandy Land is affected by wind erosion and sand burial, the Gurbantungut Desert is affected by seasonal snowmelt and other factors, the forests along the Tarim

Table 1. Hierarchical structural system and cross-scale functions of desert ecosystems.

Scale	Structural components	Key functions	Representative examples
Microscale (μm -mm)	Soil microbial communities and viruses	Nutrient cycling, decomposition and carbon transformation	Cyanobacteria, bacteria and soil viruses in crust-associated soils [16, 37]
Mesoscale (cm-m)	Biological soil crusts	Soil stabilization, carbon and nitrogen inputs, infiltration regulation	Lichen-moss and cyanobacterial crusts in Chinese sandy lands [10, 12, 15]
Plot scale (m-10 m)	Individual shrubs and fertile islands	Resource accumulation beneath canopies and microbial activity enhancement	Shrub fertile islands and <i>Caragana korshinskii</i> nebkhas [13, 14]
Patch scale (10-100 m)	Vegetation patches and bare interspaces	Self-organization, water redistribution and threshold dynamics	Spotted, banded and shrub-grass mosaics [17-19]
Landscape scale (km)	Desert-oasis ecotones and riparian corridors	Regional carbon-water regulation and habitat connectivity	Tarim River riparian forest and ecological water conveyance [23-25]

River are affected by factors such as groundwater, and rainfall is not the only driver of Turing instability [6, 23, 25].

There are four obvious deviations from the classic assumptions that should not be ignored. Actual deserts show substantial differences in characteristics such as soil texture and salt content; precipitation occurs in random pulses, and extreme drought causes productivity to be underestimated to a greater extent than indicated by the greenness index [5, 21]; groundwater and snowmelt make vegetation dynamics less closely related to rainfall during the same period; human activities such as grazing impose sudden and spatially structured impacts [6, 23]. Models of Chinese deserts need to incorporate various factors such as sand transport while also testing whether increasing complexity can optimize out-of-sample prediction [6, 20, 23].

Ecohydrological Processes and Water-Resource Constraints

In the desert ecosystem, the availability of water resources is a key constraint on the structure, pattern and related processes of this system. Soil moisture plays a regulating role in seedling growth, microbial activity, crust restoration, evaporation, water flow and water replenishment. Antecedent moisture conditions influence the duration and extent of carbon uptake after the pulse [5, 22]. Field sensors, satellite outputs and multi-scale models can provide complementary information, but it is still difficult to quantify uncertainty in rough surfaces, crusts, patchy vegetation and areas with different soil textures [22]. Ecohydrology must distinguish between short-term surface wetting and deep soil moisture available to plants or water supplied by groundwater.

The deserts along the rivers in northwest China highlight the importance of the interrelationship between plants and groundwater. Ecological water conveyance is carried out in the lower reaches of the Tarim River to raise the groundwater level and thus promote vegetation

restoration. However, there are differences in the degree and persistence of the response in different regions, and the groundwater level needs to be maintained within the range that can be tolerated by phreatophytes such as *Populus euphratica* [23-25]. Groundwater can buffer meteorological droughts. However, recoverable irrigation, vegetation expansion, and competing regional uses may deplete the same reserve [23]. The increase in vegetation cover in the short term cannot guarantee that long-term hydrological conditions can be maintained.

This combination creates a restoration trade-off. Increasing shrub or tree cover can reduce wind erosion of the soil and increase biomass, but if it is too dense, it will increase transpiration, consume deep water, and thus reduce recharge [23, 33]. In semi-arid sandy lands, the restoration of herbs is closely related to intermittent rainfall; the survival of extremely arid riparian corridors is largely dependent on groundwater. Restoration targets need to be determined according to water balance and vegetation carrying capacity rather than just focusing on planting area. The minimum monitoring scope should cover precipitation, profile soil moisture, plant transpiration, runoff, groundwater depth, plant water uptake, and patch layout [22, 23, 33]. Table 3 presents the ecological and hydrological comparison.

Carbon Cycling, Biological Soil Crusts and Restoration Trade-Offs

Historically, the ability of desert ecosystems to store carbon is relatively weak, but carbon uptake in arid lands influences the trend of terrestrial carbon sinks and interannual variation [4, 5]. In the desert regions of northern China, the storage of soil organic carbon and nitrogen varies with aridity gradients and differences in particle-size composition, biological soil crust cover affects the input of carbon and nitrogen [38], and surface communities are important in arid land carbon accounting [39]. However, many productivity data products and land surface models have not fully

Table 2. Major discrepancies between classical vegetation-pattern models and field realities in dryland ecosystems.

Issue	Classical model assumption	Field realities in drylands	Implications for future models
Soil heterogeneity	Uniform soil texture and isotropic water movement	Texture, salinity, biological crusts, and microtopography vary strongly	Couple reaction-diffusion models with spatial soil layers and crust modules
Precipitation regime	Stable or smoothly changing rainfall input	Rainfall occurs as pulses; drought impacts are non-linear [21]	Add stochastic rainfall and drought memory functions
Groundwater dependence	Vegetation mainly uses rainfall-derived soil water	Riparian deserts depend on groundwater and ecological water conveyance [23-25]	Add groundwater-depth and plant water-use modules
Aeolian processes	No explicit sand movement or burial	Dune mobility reshapes seedling survival and patch persistence [6]	Integrate wind erosion, sand deposition and surface roughness
Human disturbance	Grazing and infrastructure are external disturbances	Grazing, afforestation and photovoltaic construction reshape feedbacks [28, 31, 35]	Develop agent-based human-activity and infrastructure modules

Table 3. Conceptual ecohydrological comparison among major desert ecosystem types.

Hydrological component	Hyper-arid desert	Semi-arid sandy land	Riparian desert-oasis ecotone
Main water source	Rare precipitation and episodic runoff	Precipitation pulses and shallow soil moisture	Groundwater and ecological water conveyance
Dominant water loss	Evaporation from bare surfaces	Evapotranspiration by shrubs and herbs	Transpiration by phreatophytes and evaporation from river corridors
Key ecological structure	Sparse shrubs and biological crust patches	Shrub-grass mosaics, dunes and fertile islands	<i>Populus euphratica</i> corridors and groundwater-dependent shrubs
Main restoration risk	Low establishment success	Soil-water depletion under high vegetation density	Groundwater decline and failure of riparian recovery
Recommended monitoring	Surface stability, crust cover, and rainfall-runoff response	Soil moisture, vegetation pattern, erosion, and carbon-water balance	Groundwater depth, vegetation vitality, and water allocation

represented the dynamic processes restricted by water and driven by pulses, so it is necessary to evaluate carbon benefits, water costs and uncertainties [5].

Satellite monitoring has detected that large-scale greening has occurred in China, and this is partly due to land-use management [26]. When the vegetation structure matches the local climate and soil moisture, shelter forests and afforestation measures can reduce wind erosion of soil, reduce soil loss, and increase carbon storage [27, 28]. However, the continuous increase in woody plant cover may not be sustainable in the long term. The situation in the Loess Plateau shows that vegetation restoration may reach the limits of local water resources, highlighting the widespread limitations of carbon-centered planting in drylands [33]. Factors such as species selection in the “Three-North” shelter forest area should be evaluated according to hydrological carrying capacity, rather than using unified greening goals.

Climate warming makes carbon-water coupling more complex. Experimental warming may have different impacts on aboveground and belowground functions, and forest canopy indicators may not reflect synchronous changes in soil carbon, nutrients and belowground biomass [29]. Shrub encroachment and nitrogen deposition can alter plant traits and thereby cause functional changes, and such changes cannot be simply attributed to net productivity [3, 30]. The carbon neutrality issue is not only about the amount of carbon stored but also about whether the gain can be sustained without impairing soil moisture or other conditions [5, 33].

Human Disturbance, Grazing and Renewable-Energy Development

Human activities and climate-related pressures jointly alter the structure and function of deserts. Grazing alters plant species composition, compacts soil, contributes to seed dispersal, redistributes nutrients, and triggers competition between shrubs and grasses, and its impact varies with spatial scale and herbivore species,

which is in line with extensive evidence that grazing pressure and biological characteristics jointly regulate aridland functions [31]. Models need to represent livestock species, seasons, intensities, and movement between patches, rather than using a single and spatially uniform disturbance coefficient [3].

The development of renewable energy has become a key driver of changes in desert conditions. Photovoltaic devices alter radiation and other microclimatic conditions, and the corresponding vegetation response varies with factors such as drought [32, 35, 36]. The construction process may involve vegetation clearance, and careful management of vegetation cover can improve microclimatic conditions [34-36]. Greening within these facilities cannot be automatically classified as an ecological benefit, and baseline data, comparison sites, and long-term monitoring of crusts are required for ecological assessment [35, 36].

To achieve the dual carbon goal, carbon sequestration and renewable energy production need to be aligned with the carrying capacity of arid lands. Regional goals can be achieved through afforestation, grazing control, ecological water diversion, and photovoltaic construction, but various intervention measures will cause the spatial redistribution of water, energy, organisms, and disturbance factors. Management should identify the conditions that can promote crust restoration, create fertile islands, and improve water use efficiency, as well as the conditions that will lead to increased water demand, habitat destruction, and soil surface instability [33, 35, 36]. This requires multidimensional evaluation rather than just assessing carbon, energy, and ecological outcomes.

Toward Hybrid Observation-Modeling Frameworks

A major scientific gap is the shortage of long-term, co-located measurements linking vegetation-pattern change, profile soil moisture, groundwater, crust development, microbial function, and carbon flux [5, 22, 23]. Remote sensing offers spatial continuity but limited

access to subsurface mechanisms; field observations provide mechanistic detail but sparse coverage. The integrated observation system needs to integrate satellite SIF, vegetation indices, UAV multispectral and lidar data, soil moisture profiles, groundwater wells, eddy covariance measurements, and microbial and viral observations. Viruses in the soil may regulate microbial survival strategies and the carbon cycle, and it is necessary to expand models beyond interactions between plants and water [16, 37].

Future dryland models need to have both process-related and decision-relevant characteristics. Reaction-diffusion models are still valuable for testing feedback mechanisms, but their predictions need to be incorporated into a framework that includes factors such as stochastic rainfall [5, 20]. Machine learning such as data assimilation can connect modules with

observations, and the models need to be verified in different desert types and also report uncertainties and potential failure conditions. Fig. 2 presents a framework that combines observations and modeling.

In practical terms, the structure-pattern-process framework transforms assessment from static greenness into dynamic diagnosis. Managers need to consider whether intervention measures can restore a stable soil surface, maintain a sustainable water balance, restore the functions of crusts and microorganisms, continuously store carbon, and maintain resilience during drought [6, 23, 33]. Similarly, for renewable energy sites, there is a lack of causal and long-term evidence on ecological conditions, and installed capacity and vegetation cover alone are insufficient [35, 36]. Such assessments can reduce restoration failures, water consumption, and degradation caused by infrastructure.

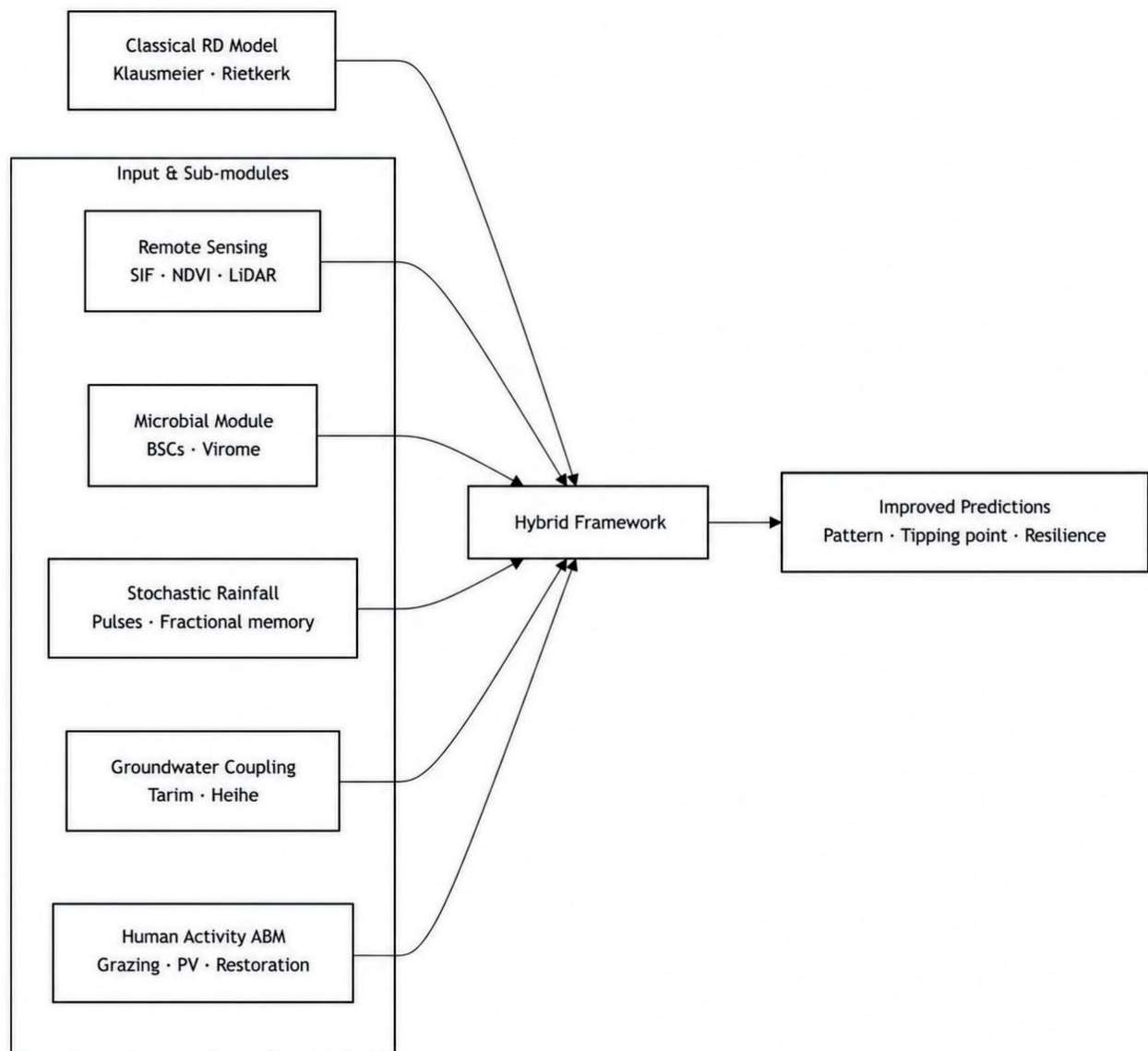


Fig. 2. Hybrid observation-modeling framework for desert ecosystems. Classical reaction-diffusion theory is integrated with remote-sensing observations, field monitoring, stochastic precipitation, groundwater dynamics, microbial processes, grazing, ecological restoration, and renewable-energy development modules.

Priority Scientific Questions for Future Research

Future research needs to determine how interactions between microscopic organisms extend to dynamics at the patch and landscape scales, link microbial composition with infiltration and nutrient-related processes through nested manipulation experiments, measure spatial co-localization, and thereby distinguish simple correlations from causal pathways [3, 6, 16].

The hydrological thresholds that define successful recovery and water depletion conditions need to be identified. Comparative studies should examine water use by specific species and at different densities, deep soil-water recovery trends, groundwater thresholds, residual impacts of drought, and recharge under different climate gradients. To determine whether recovery benefits persist beyond unusually wet years or short-term project evaluations, long-term soil-profile measurements, stable isotope analysis, stem sap-flow monitoring, and observations of groundwater wells and fluxes are required [23, 25, 33].

Spatial patterns need to be comprehensively evaluated to indicate ecosystem resilience or transformation. Prospective research needs to distinguish between pattern indicators and functional changes while identifying the roles of factors such as self-organization and topography. Models need to clearly identify the mechanisms of pattern generation and the impact of boundary conditions on early warning, delay, or avoidance of critical states [18–20].

The causal ecological effects of desert photovoltaic development throughout its life cycle need to be determined. Before-after-control-impact designs, matched reference sites, and standardized monitoring should be implemented from construction through operation and decommissioning. Research should jointly quantify biological soil-crust disturbance, runoff redistribution, soil carbon, vegetation composition, wildlife movement, and climatic confounding instead of inferring benefits or harm from a single post-construction greenness measurement [34–36].

Observations and models should support management decisions that balance carbon sequestration, water availability, biodiversity conservation, and energy production. Transferable predictions require harmonized measurements, open time-series datasets, cross-desert validation, process-constrained data assimilation, and explicit uncertainty assessment. The decisive test is whether a model can identify robust intervention portfolios and hydrological limits under climatic conditions and management regimes that were not used for its calibration [5, 28, 33].

Conclusions

This structured synthesis of 39 publications shows that the desert ecosystems of arid China are best understood as coupled systems in which microbial

communities, biological soil crusts, fertile islands, vegetation patches, dunes, riparian corridors, and landscape mosaics regulate one another through water, nutrient, carbon, and disturbance feedbacks. Evidence supports cross-scale interpretation and shows that vegetation cover is not a comprehensive indicator of ecological conditions. Water availability is a key limiting factor. Precipitation pulses, antecedent soil moisture, plant water loss, and groundwater levels jointly affect whether the system moves toward resilient recovery or experiences delayed water shortage. Therefore, restoration goals should include measurable water-balance and carrying-capacity targets, especially in riparian desert areas that depend on groundwater.

Classic vegetation pattern models demonstrate feedback mechanisms and potential transitions. However, when applying them to Chinese deserts, it is necessary to consider factors such as soil heterogeneity, wind-induced material transport, snowmelt, groundwater conditions, rainfall variability, and disturbance from human activities. Spatial patterns should be regarded as indicators of underlying mechanisms and resilience, not as universal early warning signs, and require prospective verification against functional changes. Future research needs to focus on cross-scale causal experiments, hydrological thresholds, model-index validation, full life-cycle assessment of photovoltaic infrastructure, and testing hybrid models for individual desert systems. Carbon neutrality strategies should be evaluated in terms of sustained carbon storage, water-resource use, biodiversity conservation, soil-surface stability, and improved resilience to drought, rather than only in terms of greening area or installed energy capacity.

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Conflict of Interest

The authors declare no conflict of interest.

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