



Soil Memory and Dryland Restoration Failure: Legacy Effects, Functional Thresholds, and Recovery Pathways

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Abstract: Restoration projects in drylands fail in more than one way: some never establish, some decline after early success, and some gain vegetation cover while soil and hydrological functions remain impaired. Across 174 dryland seeding sites worldwide, 17% established none of the species sown, and seeded-species occurrence declined as projects aged. This review examines whether persistent soil legacies can help explain part of this variation. Soil memory is used here in a restricted sense: a soil-resident imprint of past degradation, disturbance, management, or climatic stress that can be linked to degradation history, persists beyond short-term or seasonal variability after the original pressure has declined, and can modify the response to restoration. Evidence from soil science, dryland ecology, ecohydrology, restoration ecology, and rangeland research is synthesized against this definition. The review uses a purposive, mechanism-based synthesis rather than a systematic review or meta-analysis, and SMRF remains a framework for prospective testing rather than a validated decision model. Six domains are distinguished: chemical, physical, biological, hydrological, management-imprinted, and coupled memory. Current grazing, tenure, access, enforcement, and maintenance are treated separately as feasibility conditions. Five failure patterns are identified, ranging from immediate establishment failure to implementation failure. The Soil Memory-Based Restoration Framework (SMRF) is proposed as a diagnosis-led sequence that links soil-memory classification, threshold assessment, feasibility screening, and restoration pathway selection. Remote sensing supports screening and stratification, while soil-memory classification requires field or laboratory confirmation. Where a historical reference state is no longer feasible under current and projected climate, SMRF separates recovery of soil function from endpoint feasibility. Indicators and published numerical values are used as locally

interpreted screening evidence rather than universal thresholds. The framework may therefore help restoration planning distinguish visible recovery from recovery of the soil, hydrological, biological, and vegetation functions needed for persistence.

Key words: Soil memory, dryland restoration, legacy effects, functional thresholds, restoration failure, ecosystem recovery.

Abbreviations: BSC, biological soil crust; DEM, digital elevation model; EC, electrical conductivity; ECe, electrical conductivity of the saturation extract; ESP, exchangeable sodium percentage; EVI, enhanced vegetation index; NDVI, normalized difference vegetation index; SAR, sodium adsorption ratio; SAVI, soil-adjusted vegetation index; SMRF, Soil Memory-Based Restoration Framework; SOC, soil organic carbon.

Drylands occupy a substantial proportion of the Earth's terrestrial surface and support pastoral, agricultural, conservation, and urban systems that operate under persistent water limitation, high climatic variability, fragile soil surfaces, and slow biological recovery (Noy-Meir, 1973; Whitford, 2002; Prävälle, 2016). Their vulnerability has been recognized for decades in dryland ecology, soil science, and desertification research, where rainfall pulses, resource islands, vegetation–soil feedbacks, and surface stability determine how these ecosystems function, persist, and degrade (Schlesinger *et al.*, 1990; Reynolds *et al.*, 2007; Maestre *et al.*, 2021). In response, global restoration efforts have expanded through land degradation neutrality, rangeland rehabilitation, assisted natural regeneration, revegetation, water harvesting, soil conservation, and carbon-oriented recovery programs (Daily, 1995; Whisenant, 1999; MEA, 2005; Aronson and Alexander, 2013; UNCCD, 2017; IPBES, 2018; Gann *et al.*, 2019). Yet restoration outcomes in drylands remain strikingly uneven. The same intervention may succeed in one site, fail in a nearby site, or produce short-lived greening followed by decline.

A similar restoration treatment can produce different outcomes because sites differ in both inherited soil condition and current implementation pressure. A bare or sparsely vegetated surface may retain salinity, sodicity, compaction, crusting, shallow rooting depth, depleted propagules, altered soil biota, or

runoff connectivity. Ongoing grazing, access, or maintenance problems can add a separate constraint. Keeping the inherited constraint separate from the current one makes it clearer why a treatment succeeds at one site and fails at another.

Conventional restoration planning often begins with the symptom that can be seen: sparse vegetation, exposed soil, sand movement, or erosion features. The response then becomes planting, seeding, exclusion, water harvesting, or amendment application. This intervention-centred logic can work where degradation is shallow, recent, and reversible. It becomes weak when it does not ask why the site lost its function, which soil properties still carry that history, and whether the proposed intervention can overcome those inherited constraints. Restoration ecology has shown that alternative states, positive feedbacks, hysteresis, and thresholds can prevent passive recovery even after the original disturbance has been reduced (Friedel, 1991; Laycock, 1991; Suding *et al.*, 2004; Briske *et al.*, 2005; Suding and Hobbs, 2009). Soil science has also shown that salinity, sodicity, compaction, crusting, organic matter depletion, and loss of soil biota can persist long after disturbance and continue to shape ecological function (Sumner, 1993; Doran and Zeiss, 2000; Belnap, 2003; Rengasamy, 2006; Batey, 2009; Bünemann *et al.*, 2018). What remains underdeveloped is an operational framework that treats these persistent edaphic legacies as diagnostic memory rather than isolated soil constraints. Soil memory is defined here by four conditions: the property can be traced to a history of degradation, disturbance, management or climatic stress; it can be measured in the soil or in the hydrological behavior of the surface; it persists after that pressure has declined; and it changes what a restoration intervention achieves. These effects are expressed through soil-surface and root-zone processes such as infiltration, rooting depth, nutrient availability, safe-site formation, and propagule retention. The conceptual foundation below sets out each condition and what it excludes.

In drylands, vegetation can respond quickly to a wet season while these functions remain impaired (Tongway and Ludwig, 1996; Schlesinger and Pilmanis, 1998). Planting can also establish initially and decline later where

sodicity, compaction, shallow rooting depth, or depleted propagules still limit recovery. These examples show how chemical, physical, biological, hydrological, management-imprinted, and coupled legacies can shape restoration response (Bestelmeyer *et al.*, 2015; Monger *et al.*, 2015; Coban *et al.*, 2022).

Soil memory is not the only reason dryland restoration fails. Rainfall during establishment, seed viability and provenance, species-site matching, sowing rate, sowing date, and post-planting maintenance can all affect recruitment (Copeland *et al.*, 2025; Sowards *et al.*, 2025). A global analysis of 174 dryland seeding sites identified seeding rate, seed mass, and site aridity as important predictors and found that 17% of projects had no establishment of any seeded species (Shackelford *et al.*, 2021). The narrower question examined here is whether persistent soil legacies add explanatory value when restoration outcomes differ among sites and those legacies have not been measured before intervention.

This review develops soil memory as an operational diagnostic concept for dryland restoration. It brings together evidence on persistent chemical, physical, biological, and hydrological legacies and examines how these legacies can alter restoration response. The central step is to move from describing present soil condition to identifying which measured conditions retain an effect of past degradation, whether that effect is strong enough to restrict recovery, and what this means for intervention choice. The Soil Memory-Based Restoration Framework (SMRF) then connects this diagnosis with functional thresholds, restoration failure patterns, intervention selection and sequencing, and monitoring. In this way, degradation history becomes part of the explanation for present restoration constraints and part of the evidence used to decide what should be done next.

Review methodology and evidence synthesis:

A meta-analysis was not appropriate here. Dryland restoration studies differ in climate, soil, degradation history, intervention design and monitoring duration, and a pooled effect size would average away the differences this review sets out to examine. Instead, the review develops a mechanism-based synthesis that links inherited soil constraints to restoration

outcomes, failure pathways, threshold behavior, and decision logic.

Literature identification drew on Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, and Taylor & Francis, with Google Scholar used as a supplementary discovery source. Searches covered literature available through August 2026, while earlier foundational studies were retained where they remained directly relevant to the concepts and mechanisms examined. The core search combinations are reported in Supplementary Table S1.

Sources were selected purposively for their relevance to mechanisms linking dryland degradation, persistent soil constraints, and restoration response. Eligible evidence included peer-reviewed empirical studies, theoretical papers, major reviews, foundational soil-science literature, restoration standards, methodological studies, and authoritative reports. Sources with no clear dryland relevance, purely agronomic yield trials without restoration interpretation, inaccessible or unverifiable material, and studies lacking relevant soil, hydrological, biological, vegetation, geospatial, or management information were excluded.

Selection was purposive and is not claimed to be exhaustive. Retrieval counts were not logged during the search, so screening-flow totals are not reported. The synthesis was structured using the categories shown in Supplementary Table S1, including evidence field, soil-memory domain, geographic context, degradation legacy, intervention type, outcome pattern, threshold logic, and monitoring approach. These categories were used as an organizing framework for interpretation rather than as an item-level systematic-review database. Supplementary Table S1 reports the search architecture, eligibility criteria, and coding framework.

The evidence synthesis was organized around five broad evidence fields: dryland ecology, restoration ecology, soil chemistry and physics, biological memory, and geospatial monitoring. This structure supports the central argument of the review: substantial evidence exists on dryland degradation, restoration failure, soil constraints, biological soil crusts, seed-bank dynamics, and remote sensing, but these bodies of work are rarely brought

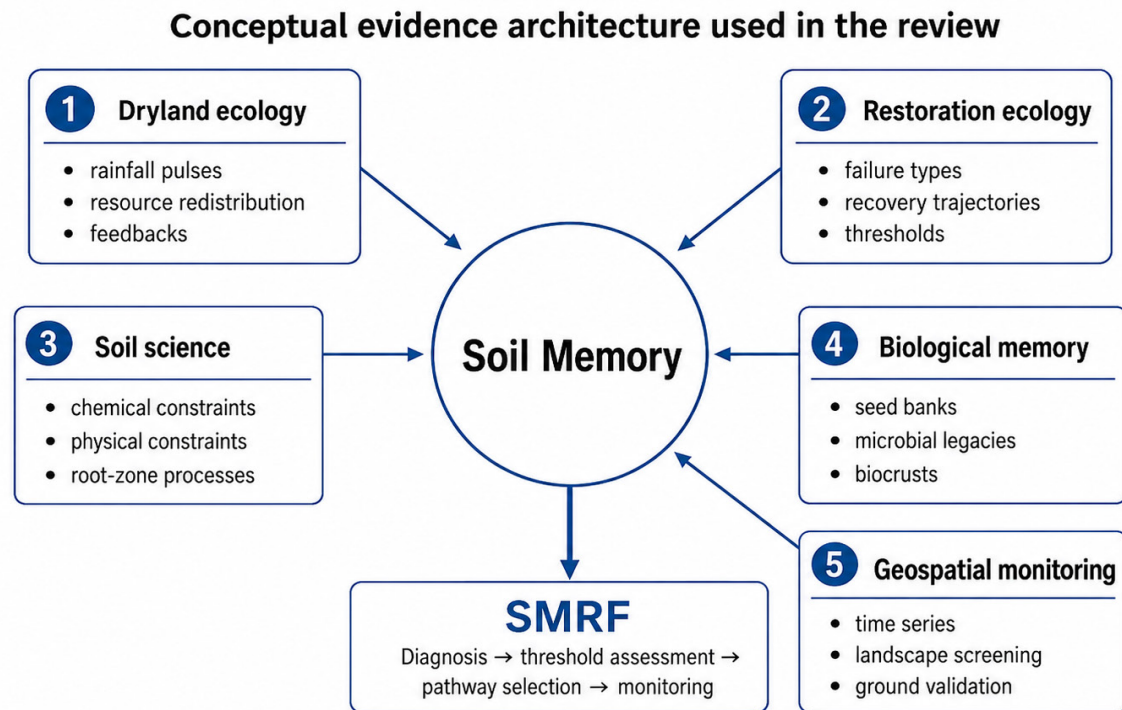


Fig. 1. Author-constructed conceptual evidence map showing the links used in this review among dryland ecology, restoration ecology, soil science, biological memory, and geospatial analysis. Node placement and links are illustrative and do not represent bibliometric or citation-network results.

together into a single diagnostic framework for explaining restoration failure. The Soil Memory-Based Restoration Framework (SMRF) was developed to address this gap by linking soil diagnosis, threshold assessment, restoration pathway selection, and monitoring within one operational sequence.

Supplementary Table S2 sets out what each of the five fields contributes and which gap SMRF addresses in it. Figure 1 shows how these fields connect in the synthesis.

Conceptual foundation: what is soil memory? Soil memory is the soil-resident, persistent, and intervention-relevant part of a site's degradation history, expressed in soil properties and in the hydrological behavior of the surface. In SMRF, the unit of classification is a functional soil-landform unit within the restoration site, not an individual soil sample or the entire project by default. A functional unit is a spatially coherent area in which soil condition, surface processes, hydrology, and degradation history are sufficiently similar to support one diagnosis and intervention pathway. Depending on site heterogeneity,

it may represent a microsite, plot, hillslope segment, or management subunit. Soil-profile and surface measurements are used to characterize that unit; they are not themselves separate classification units. Larger restoration sites may therefore contain several soil-memory classes. The definition excludes reversible weather anomalies and applies only to degradation-linked properties that can influence restoration response. Restoration is used here as the general term; rehabilitation is used where the objective is recovery of selected functions rather than return to a historical reference state (Gann *et al.*, 2019).

The idea of soil memory has developed through several related lines of research. The concept has earlier roots in pedology, where soil memory was developed as the capacity of soil to retain records of past environmental conditions and pedogenic processes through different carriers, hierarchical levels, and forms of record (Targulian and Goryachkin, 2004; Targulian and Bronnikova, 2019). Studies of dryland legacies showed that past conditions can continue to influence present ecological, soil, and geomorphic properties over periods

ranging from days to millennia, with the strength of the legacy depending on the original event, the time elapsed, and the sensitivity of the system (Monger *et al.*, 2015). Janzen (2016) described soil as a long-lived archive in which environmental and management history remains recorded in physical, chemical, and biological properties. Lapsansky *et al.* (2016) applied soil memory to persistent plant-microbiome interactions that can influence later plant performance. More recently, Rahmati *et al.* (2023) described soil memory in terms of both abiotic and biotic carriers, including soil structure, organic matter, moisture, biological communities, and molecular records, through which past conditions can influence later hydrological, biogeochemical, and biological responses.

In this review, soil memory is used as a diagnostic construct that connects a past driver with a persistent soil imprint and a later functional response. A measurement of salinity, compaction, soil organic carbon, microbial condition, or infiltration describes the soil at the time of measurement. Soil memory adds a temporal and functional question: does that condition retain an effect of earlier degradation, and can that retained effect change the response to restoration? The distinction therefore lies in the link between degradation history, persistence, and subsequent function rather than in the soil variable alone.

This also separates soil memory from related concepts. Soil health and soil quality describe present functional condition (Doran and Zeiss, 2000; Karlen *et al.*, 2003; Bünemann *et al.*, 2018), whereas legacy effects include persistent influences of past events across different parts of an ecosystem (Foster *et al.*, 2003; Cramer *et al.*, 2008; Monger *et al.*, 2015; Nieland and Keiser, 2025). Ecological memory addresses the broader capacity of an ecosystem to respond and reorganize after disturbance (Padisák, 1992; Schaefer, 2009; Johnstone *et al.*, 2016), while hysteresis describes a recovery pathway that differs from the pathway of degradation (Friedel, 1991; Suding *et al.*, 2004; **Suding** and Hobbs, 2009). Soil memory, as used here, focuses on the measurable soil-resident part of past disturbance that remains relevant to a restoration decision. The criteria below provide the operational test for identifying when a measured condition belongs to this category.

A soil property is treated here as soil memory only when four conditions are met. First, it can be linked to a documented or evidence-supported history of degradation, disturbance, management, or climatic stress rather than to inherent site variation alone. Second, it can be measured in the soil, at the soil surface, or through the hydrological behavior of the functional unit. Third, persistence should be supported by repeated observations, chronosequence evidence, or published evidence showing that the effect remains detectable after the causal pressure has been reduced or removed and beyond the normal short-term or seasonal variability of the site. No single duration is imposed because recovery time differs among soil processes; the relevant test is whether the effect persists long enough to influence a subsequent restoration decision or response. Fourth, site-specific evidence or empirical evidence from comparable dryland systems should show that the retained condition is capable of modifying restoration response; direct demonstration of that effect at the focal site is not required before classification. These conditions separate soil memory from transient environmental variation and from inherent soil properties that were not produced by degradation history.

Where direct historical records are unavailable, degradation history may be inferred from converging evidence. Suitable evidence includes time-series satellite or aerial imagery, land-use or irrigation records, documented grazing or cultivation history, erosion and sediment-redistribution features, persistent traffic or disturbance patterns, soil-profile evidence consistent with a known degradation process, and comparison with suitable reference sites or chronosequences. A single low soil value or one current field observation is not sufficient to establish degradation history. Where degradation history is inferred rather than documented, classification should be supported by at least two independent lines of evidence. With only one indirect line of evidence, the condition should remain a candidate constraint pending confirmation rather than be assigned as soil memory.

Some conditions therefore fall outside soil memory even when they influence restoration. A single low-rainfall year is a climatic condition

Table 1. Soil memory in relation to adjacent concepts

Concept	Locus	Time reference	Diagnostic question	Why it is insufficient alone
Current soil condition	Soil profile	Present	What is the soil like now?	Gives no information on reversibility
Soil health / soil quality	Soil profile	Present, against a benchmark	Is the soil functioning adequately?	Describes present functional condition but does not by itself identify the origin, persistence, or intervention relevance of a degradation legacy.
Legacy effect	Any compartment	Past driver(s) or land-use history	What did event X leave behind?	Broad concept; does not by itself identify which soil-resident legacy controls intervention response
Ecological memory	Whole ecosystem	Past disturbance regime	Can the system reorganize itself?	Broader than the soil compartment and not designed specifically to identify intervention-relevant soil legacies.
Hysteresis	System trajectory	Path dependence	Does recovery retrace degradation?	Describes behavior, not the causal property
Restoration potential	Site	Future	How much recovery is possible?	An output, not a diagnosis
Soil memory (this review)	Functional soil-landform unit, characterized by soil-profile, surface, and hydrological measurements	Past and cumulative; single or interacting drivers	Which measurable soil or surface properties still carry degradation history, and can they modify the response to a given intervention?	Requires evidence of historical linkage and persistence, together with local calibration

Note: The rows are not mutually exclusive. Soil memory is the subset of legacy and ecological-memory phenomena that is resident in the soil, persistent, and intervention-relevant, and is therefore the subset a restoration team can act on before planting

rather than a persistent soil legacy. Surface soil moisture after a rainfall event is measurable but transient. Inherent properties such as parent material, natural texture, or coarse-fragment content may strongly affect intervention choice, but they are not soil memory unless past degradation has altered them or their functional expression. They remain part of site diagnosis rather than degradation memory.

These tests also define what is outside the concept. Tenure, enforcement capacity, fencing, access, and project duration are not soil memory because they are current institutional or management conditions rather than measurable soil properties. Past management can, however, leave persistent soil or surface residues such as compaction, crust fragmentation, connected bare interspaces, traffic tracks, or depleted propagules. SMRF diagnoses those residues as soil memory and records current management conditions separately as feasibility factors. Table 1 summarizes this distinction.

This concept is especially important in drylands. Recovery in these systems is often slow because water is limiting,

primary productivity is low, organic matter accumulation is constrained, and microbial and plant processes respond strongly to episodic rainfall pulses (Noy-Meir, 1973; Huxman *et al.*, 2004; Austin, 2011; Schimel, 2018). Dryland soil surfaces are also biologically and physically fragile. Biological soil crusts, for example, may take long periods to recover after disturbance (Eldridge and Greene, 1994; Belnap and Eldridge, 2003; Bowker, 2007), especially where trampling, erosion, fire, or repeated drought continue to affect the surface (Duniway *et al.*, 2019). For this reason, vegetation greening alone can be misleading. A site may show improved cover after a wet season while still retaining compacted layers, poor infiltration, depleted seed banks, weak microbial function, or unstable soil surfaces. The two can be measured separately, and in drylands they routinely diverge.

A degraded site may appear to improve after a favorable rainfall year, but the underlying constraint may remain unchanged if infiltration, rooting depth, sodium dispersion, seed-bank density, or microbial function have not

recovered. Conversely, a site may show little immediate vegetation response but still contain recoverable soil structure, viable propagules, and enough hydrological function to support recovery once pressure is reduced. Restoration planning becomes more precise when these differences are recognized before interventions are selected.

State-and-transition models describe possible ecosystem states, transitions, and the processes that maintain them (Briske *et al.*, 2005; Briske *et al.*, 2008). SMRF asks a narrower question: whether persistent soil and surface constraints help explain why a particular transition is blocked or requires intervention. A transition threshold may involve soil memory, vegetation feedbacks, climate, management, or several processes acting together. SMRF therefore does not redefine all state-and-transition thresholds as soil memory; it identifies the soil-resident component where one exists and links it to measurable indicators.

Domains of soil memory in drylands: Across all six domains, a measured condition is treated as soil memory only when it satisfies the historical-link and persistence criteria defined in the conceptual foundation of this review. Where those criteria are not met, the measurement remains part of current site diagnosis rather than evidence of soil memory.

i. Chemical memory: Chemical diagnosis in this review uses electrical conductivity of the saturation extract (ECe) as the preferred salinity measure, sodium adsorption ratio (SAR) as an index of soluble sodium hazard, and exchangeable sodium percentage (ESP) as an indicator of exchangeable sodium status. Where electrical conductivity (EC) is reported using another soil-water extraction method, the method should be stated explicitly and the value should not be treated as directly interchangeable with ECe.

Chemical memory refers to persistent chemical conditions that remain after the original degradation or management pressure has been reduced or removed. It includes salinity, sodicity, altered pH, carbonate buffering, nutrient depletion, and changes in soluble ions or potentially toxic elements. Drylands concentrate these constraints: high evaporative demand and limited leaching hold salts and sodium in the root zone (Rengasamy,

2006; Daliakopoulos *et al.*, 2016), and shallow or saline groundwater and poorly drained irrigation add to them (Qadir *et al.*, 2007; Corwin and Scudiero, 2019; Corwin, 2021; Hopmans *et al.*, 2021; Demo *et al.*, 2025; Daba, 2025). Salinity can restrict plant water uptake through osmotic stress, while sodicity can disperse clay, weaken aggregates, reduce infiltration, and promote surface sealing (Sumner, 1993). When these processes occur together, germination, rooting, and effective use of rainfall may all be reduced.

Salt and sodium legacies should not be treated like ordinary nutrient deficiencies. A nutrient deficiency can often be corrected through addition when moisture, rooting depth, and soil structure are adequate. Salinity and sodicity require a different logic because salts and sodium must be displaced, exchanged, leached, drained, diluted, or isolated from sensitive root zones. Seeding or planting before diagnosing salt accumulation, sodium dispersion, or drainage limitation often produces immediate failure, or a delayed failure that appears only after the first drought or irrigation cycle. In a saline surface horizon, germination may fail even after rainfall because the osmotic potential of the soil solution remains unfavorable. In a sodic clay or clay loam, water-harvesting structures may capture runoff but still fail to support vegetation if the captured water cannot infiltrate or if dispersed clay seals the surface after wetting. Salinity has also been associated with lower soil organic carbon (SOC) stocks, linking persistent chemical stress with biological soil condition (Setia *et al.*, 2013).

Alkalinity and carbonate dominance represent another important form of chemical memory in arid and semi-arid soils. High pH and carbonate accumulation can reduce the availability of phosphorus and micronutrients, especially iron, zinc, and manganese, while calcium carbonate buffering can limit the effectiveness of amendments and slow chemical adjustment (Lajtha and Schlesinger, 1988; Cross and Schlesinger, 1999; Lal, 2004). In calcareous soils, phosphorus fixation is not only a fertility issue. It can become a restoration constraint when early seedling growth depends on small, spatially available nutrient pools. Nutrient depletion adds another layer of memory. Long-term biomass removal, erosion of surface horizons, and low organic inputs reduce nitrogen, phosphorus, and biologically

mediated nutrient cycling, which can weaken early plant establishment and delay recovery of soil function (García *et al.*, 1997; Lal, 2001; Bastida *et al.*, 2015).

ii. Physical memory: Physical memory is what remains of the soil's architecture after degradation has reshaped it. It covers what restricts roots (compaction, hardpans, shallow effective depth), what blocks the surface (crusting, erosion pavement), and what removes it (wind and water erosion). In drylands and rangelands, these structural legacies often develop through livestock trampling, vehicle movement, repeated cultivation, loss of protective vegetation cover, and the direct impact of raindrops on exposed soil surfaces (Thurrow, 1991; Valentin and Bresson, 1992; Hillel, 1998; Hamza and Anderson, 2005; Batey, 2009; Nawaz *et al.*, 2013; Rabot *et al.*, 2018; Macheroum *et al.*, 2025). Once formed, they can remain active long after the original pressure has declined (Lal, 2001).

The consequences for restoration are immediate and practical. Surface crusts reduce infiltration, restrict gas exchange, and create a physical barrier to seedling emergence. Compaction increases penetration resistance, reduces macroporosity, limits root extension, and weakens the capacity of the soil to store and transmit water. Erosion removes the surface horizon that usually contains the highest concentrations of nutrients, organic matter, biological crusts, and viable seeds, leaving subsoil material, gravel pavement, or coarse fragments as the new establishment surface (Breshears *et al.*, 2003; Ravi *et al.*, 2010; Webb *et al.*, 2014). Wind erosion can selectively remove fine particles and organic matter, while water erosion can connect bare patches into runoff pathways. In this way, physical memory often turns restoration into a safe-site problem. Seeds may be available, rainfall may occur, and nutrients may still exist somewhere in the profile, but the surface may no longer be able to receive, store, or protect the resources needed for establishment.

Physical memory is also strongly scale-dependent. A degraded site may contain small microsites where establishment is possible and adjacent bare patches where the same intervention fails. This spatial contrast is central to dryland function, where vegetation patches

operate as resource islands and bare interspaces regulate runoff, sediment movement, seed redistribution, and nutrient loss (Schlesinger *et al.*, 1990; Tongway and Ludwig, 1996; Ludwig *et al.*, 2005; Turnbull *et al.*, 2008). Physical processes should be assessed at the scale of the functional soil-landform unit while accounting for hydrological and sediment connections with adjacent and upslope areas. A single bulk density value cannot replace field evidence on crust continuity, runoff connectivity, erosion form, root-restricting layers, surface roughness, and microtopographic variation.

A compacted rangeland surface after long-term grazing provides a clear example. Livestock exclusion may reduce current pressure, but it may not restore macroporosity, aggregate stability, infiltration, or safe sites within the short time frame of a restoration project. Seeding such a surface may fail not because the selected species are unsuitable, but because the soil cannot retain water around the seed or allow roots to penetrate beyond the shallow surface layer. In another setting, shallow stony soils may support scattered shrubs but fail to sustain the tree density expected by a planting campaign. These cases show why suspected physical legacies should be assessed before intervention. The diagnosis can help determine whether a physical constraint is limiting establishment, which treatment should be considered first, and whether planting is likely to succeed under the measured site conditions.

iii. Biological memory: Biological memory concerns persistent changes in biological properties that can be linked to previous degradation. Relevant measurements include SOC, microbial properties, mycorrhizal associations, native seed banks, and BSC condition. These variables are treated as soil memory only when the historical-link and persistence criteria defined in the conceptual foundation of this review are met (Requena *et al.*, 2001; Harris *et al.*, 2006; Kulmatiski *et al.*, 2008; Harris, 2009; Delgado-Baquerizo *et al.*, 2016; Hannula *et al.*, 2021).

Low SOC or weak biological activity is not, by itself, evidence of soil memory. These conditions are classified as biological memory only when they can be linked to prior degradation or disturbance and shown to persist beyond the expected range of local

spatial or seasonal variability. For example, low SOC in a naturally carbon-poor dryland soil is a current site condition; it becomes evidence of a degradation legacy only when loss relative to an appropriate reference, earlier condition, or documented disturbance history can be supported. The same principle applies to microbial activity, seed-bank condition, infiltration, and other diagnostic variables.

Microbial limitation is treated in the same way. Low microbial activity or altered community composition is not assigned to soil memory from a single measurement (Requena *et al.*, 2001; Kulmatiski *et al.*, 2008; Harris, 2009; Delgado-Baquerizo *et al.*, 2016). A microbial legacy is considered only where disturbance, invasion, land use, or another documented degradation process provides a plausible historical link and the biological change persists after that pressure declines (Hannula *et al.*, 2021; Peddle *et al.*, 2025; Wood *et al.*, 2026). Direct biological measurements are therefore required before microbial or mycorrhizal limitation is used to guide restoration.

BSCs represent one of the most distinctive forms of biological memory in drylands. They stabilize the soil surface, influence infiltration and runoff, contribute to carbon and nitrogen cycling, and create microscale heterogeneity that affects seed retention and establishment (Eldridge and Greene, 1994; Belnap, 2003; Belnap, 2006; Maestre *et al.*, 2011; Pointing and Belnap, 2012). Once disturbed, their recovery can be slow, especially under trampling, fire, wind erosion, water erosion, and recurrent extreme events (Bowker, 2007; Jech *et al.*, 2025). Their loss can therefore leave a site physically exposed and biologically simplified long after the visible disturbance has ended.

Seed-bank memory is equally important. Where native propagules have been depleted, passive recovery after grazing exclusion or disturbance removal may be slow, incomplete, or compositionally biased (Kemp, 1989; Kinloch and Friedel, 2005; Chambers *et al.*, 2007; Kushbokov *et al.*, 2025; Tlili *et al.*, 2026). A site may be protected from grazing and still fail to recover its target community if the native seed source is absent or if safe sites for recruitment have been lost. Invasion legacies add another layer of difficulty. Former invaders can leave altered nutrient pools, microbial feedbacks, and

competitive filters that continue to suppress native regeneration after aboveground removal (Belnap and Phillips, 2001; Kulmatiski *et al.*, 2008; Ehrenfeld, 2010; Perkins and Nowak, 2013; Corbin, 2025).

Protection removes pressure. It does not replace a depleted seed bank, a fragmented mycorrhizal network or a lost crust. A site with stable surfaces, viable native propagules, and functional microbial communities may recover through passive or assisted natural regeneration. A site with a depleted seed bank, disrupted microbial networks, and damaged biological crusts may require native seed addition, microsite preparation, organic inputs, biological crust protection or inoculation, and long periods without disturbance. Biological memory therefore explains why some sites appear chemically and physically suitable, yet still fail to recover the target plant community.

iv. Hydrological memory: Hydrological memory sits in the pathways rainfall follows once it reaches the surface, and those pathways persist long after the event that reshaped them. In drylands, water is the primary limiting factor (Noy-Meir, 1973; Huxman *et al.*, 2004; Wang *et al.*, 2012), but its ecological value depends less on rainfall amount alone and more on what happens after rainfall reaches the soil surface. Soil surface condition, infiltration capacity, microtopography, root distribution, patch structure, and flow connectivity determine whether a storm supports recovery or accelerates degradation (Ludwig *et al.*, 2005). Degradation can leave long-lasting hydrological legacies by reducing infiltration, increasing runoff, initiating rills and gullies, breaking down resource islands, and shortening the time that moisture remains available in the root zone (Wilcox *et al.*, 2003; Moreno-de las Heras *et al.*, 2010; Mayor *et al.*, 2013).

Hydrological memory can contribute to delayed restoration failure. A planting campaign may establish during a wet period and decline later if water does not infiltrate deeply, soil storage is limited, or runoff moves water away from planted microsites. Water-harvesting structures can show the same problem when they intercept flow but the receiving soil remains sealed, compacted, shallow, or rapidly filled with sediment. The useful distinction is between rainfall and effective water. Rainfall is

the climatic input, while effective water is the portion that infiltrates and remains available to roots and soil biota. Persistent soil and surface conditions influence that conversion.

Hydrological memory is where several soil-memory domains interact. Sodicity can disperse clay and reduce infiltration, while crusting and compaction can limit infiltration, rooting, and soil-water storage. Loss of BSCs can increase sediment movement and surface instability. Together, these processes can increase runoff, reduce establishment, maintain exposed surfaces, and strengthen erosion feedbacks. Such interactions are central to dryland threshold behavior and desertification dynamics (Schlesinger *et al.*, 1990; van de Koppel *et al.*, 1997; Rietkerk *et al.*, 2004; Kéfi *et al.*, 2007; D'Odorico *et al.*, 2013).

Hydrological diagnosis should therefore use more than annual rainfall totals. It should examine infiltration, runoff connectivity, soil-moisture persistence, microtopography, erosion features, and the performance of structures during storms. The same rainfall event can support recruitment on a stable, infiltrating surface and generate runoff on a sealed or connected bare surface. These measurements are needed before choosing water-harvesting structures, contour treatments, gully stabilization, or planting layouts.

Management-imprinted memory: Management-imprinted memory refers only to persistent soil or surface changes left by past management. Long-term grazing can leave compaction, crust fragmentation, connected bare interspaces, and depleted seed banks, while repeated traffic can leave compacted tracks that redirect runoff. These effects may persist after pressure is reduced.

A site can receive an appropriate soil or hydrological treatment and still fail if ongoing disturbance exceeds its recovery capacity. Conversely, protection may be sufficient where soil structure, propagules, and infiltration remain functional. SMRF therefore separates management-imprinted soil legacies from current management feasibility. The first is diagnosed in the soil and surface; the second is assessed through grazing control, access, tenure, enforcement, and maintenance.

Coupled soil memory: Coupled soil memory occurs when two or more persistent constraints

interact. Sodicity can promote clay dispersion and surface sealing; sealing can reduce infiltration; runoff can remove fine particles, organic matter, and seeds; and continued surface exposure can increase wind or water erosion (Schlesinger *et al.*, 1990; Okin *et al.*, 2006; Ravi *et al.*, 2010; D'Odorico *et al.*, 2013). Grazing history can also leave compaction, damaged BSCs, and depleted propagules (Rietkerk *et al.*, 2004; Bestelmeyer *et al.*, 2015; Monger *et al.*, 2015). These links can maintain degradation after the original pressure has been reduced. Table 2 sets out each domain against the diagnostic measurement and the pathway it indicates.

A single treatment may therefore leave an active constraint untouched. Seeding will not correct poor drainage, earthworks will not replace a missing seed source, and water-harvesting structures will not solve a sealed or sodic receiving soil. In a coupled system, the practical task is to identify which constraint is upstream in the failure chain and which treatments depend on it being removed first.

SMRF does not assume a fixed sequence for coupled sites. Where active runoff or erosion threatens the site, stabilization may need to come first. In other cases, a chemical or physical root-zone constraint may be the first bottleneck. Biological reassembly follows only when the site can provide suitable water, rooting conditions, safe sites, and propagule support. The sequence is therefore set by field evidence and causal dependency rather than by a universal domain order.

Three mechanisms run through the six domains. Persistence keeps the functional effect of degradation in place after the driver has gone. Coupling converts one domain into another, as when sodicity disperses clay, crusting reduces infiltration, and runoff removes the seed bank. Filtering determines whether an input becomes a function: rainfall is filtered by infiltration and storage, seed by safe-site availability, amendments by moisture and texture, and a greening signal by species composition. Soil health and soil quality describe the present condition. Soil memory asks how that condition was produced.

Functional thresholds and restoration irreversibility: Functional thresholds are points, ranges, or transition zones at which restoration

Table 2. Diagnostic domains of soil memory and recommended restoration pathways

Memory domain	Key diagnostic indicators	Persistent legacy	Main failure pathway	Recommended pathway	Monitoring focus
Chemical	ECe, or EC with extraction method reported; SAR; ESP; pH; soluble ions; nutrients; carbonate status	Salinity, sodicity, alkalinity, nutrient depletion	Osmotic stress, dispersion, nutrient limitation, and restricted rooting or establishment	Chemical-first treatment where the chemical constraint is confirmed	ECe, SAR, and ESP trends; infiltration; root-zone condition; recruitment
Physical	Bulk density, penetration resistance, crust strength and continuity, aggregate stability, effective rooting depth	Compaction, crusting, topsoil loss, shallow or root-restricting layers	Poor emergence, restricted rooting, weak infiltration, and loss of safe sites	Physical repair or safe-site creation before broad seeding where limiting	Infiltration, crust persistence, rooting depth, and surface stability
Biological	SOC; native seed bank and recruitment; BSC condition; microbial or mycorrhizal indicators where relevant	SOC loss, propagule depletion, BSC degradation, or persistent disruption of microbial or mycorrhizal function	Constraint-specific failure of recruitment, surface stabilization, nutrient cycling, or biological reassembly	Match treatment to the confirmed bottleneck: propagule support, BSC protection or recovery, or targeted microbial/mycorrhizal intervention where directly supported	Native recruitment, SOC, BSC condition, and the biological indicator used to identify the constraint
Hydrological	Infiltration, runoff response, soil-moisture persistence, flow connectivity, gully activity	Runoff dominance, connected flow paths, gully development, short moisture retention	Rainfall is lost through runoff or erosion rather than retained in the root zone	Hydrology-first treatment where runoff or moisture retention is limiting	Runoff, soil-moisture persistence, sediment movement, and erosion activity
Management-imprinted	Trampling-related compaction, crust fragmentation, persistent traffic tracks, connected bare interspaces, and other measurable residues of past management	Persistent soil or surface effects of previous management	Soil remains constrained after the original pressure has been reduced	Treat the measured soil or surface residue. Assess current grazing, access, tenure, enforcement, and maintenance separately	Soil-residue indicators together with a separate feasibility record
Coupled	Interacting indicators from two or more soil-memory domains	Linked chemical, physical, biological, hydrological, or management-imprinted legacies	One constraint reinforces or maintains another	Sequence treatment according to causal dependency and the dominant site bottleneck	Integrated soil, water, and biological response together with feasibility conditions

Note: The indicators in this table identify candidate domains for diagnosis; they do not establish soil memory by themselves. A condition is classified as soil memory only when the historical-link and persistence criteria defined in Section 3 are met. Current values that cannot be linked to prior degradation or disturbance remain site-condition indicators rather than soil-memory evidence. Evidence supporting the domain-specific diagnostic and restoration relationships is cited in Sections 4.1–4.6 and summarized in Table 3 and Supplementary Table S6. Figure 2 summarizes how degradation drivers, soil-memory domains, locally interpreted threshold evidence, pathway options, and restoration outcomes are connected within SMRF.

response changes sharply because key soil processes have shifted into a different operating state. In drylands, degradation rarely follows a smooth linear path (Holling, 1973; Friedel, 1991; Laycock, 1991; Suding *et al.*, 2004). It often advances through reinforcing feedbacks that

maintain vegetation loss, runoff dominance, crusting, erosion, salt concentration, or biological simplification even after the original driver has weakened (Groffman *et al.*, 2006; Briske *et al.*, 2008; Scheffer, 2009; Abel *et al.*, 2024). This is why a site can appear restorable

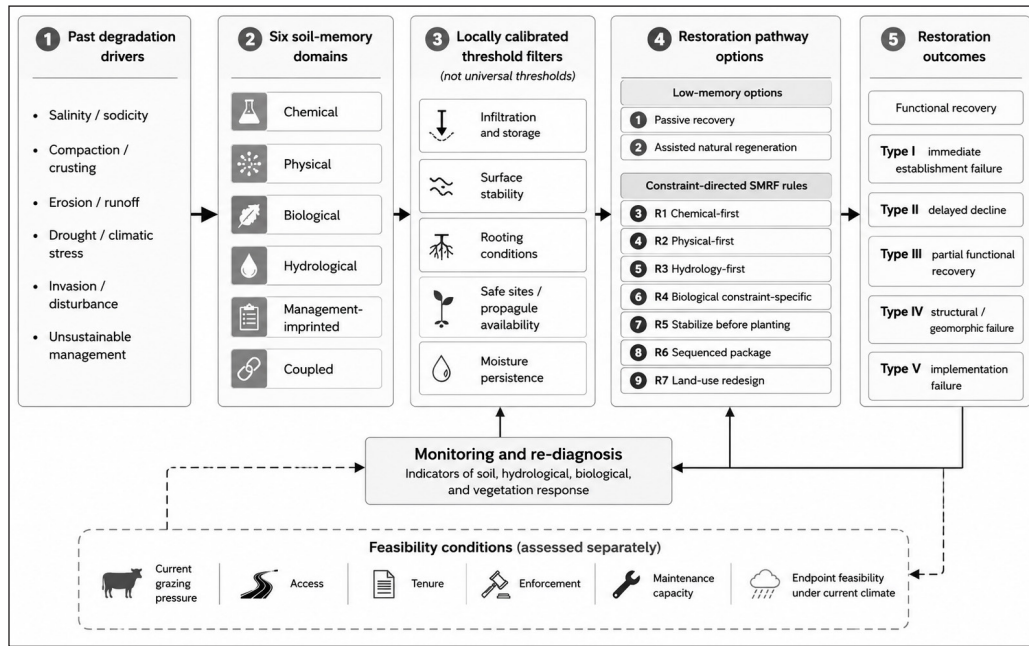


Fig. 2. Conceptual model of soil memory-driven restoration outcomes. The model links past degradation drivers, six soil-memory domains, locally calibrated threshold filters, restoration pathway options, monitoring and re-diagnosis, and restoration outcomes. Passive recovery and assisted natural regeneration are distinguished from the seven constraint-directed SMRF rules. Feasibility conditions are assessed separately from soil-memory domains.

from surface observations while still requiring intensive intervention. The visible symptom may be sparse vegetation, but the limiting condition may be a hidden threshold in soil structure, chemistry, hydrology, or biological function.

Thresholds can develop across chemical, physical, biological, and hydrological soil-memory domains. Chemical thresholds arise when salinity, sodicity, alkalinity, toxicity, or nutrient depletion restrict germination, rooting, infiltration, or nutrient uptake. Physical thresholds arise when compaction, crusting, shallow effective depth, or erosion prevent roots and seeds from using available water. Biological thresholds occur when propagule supply, BSCs, organic carbon, or microbial function become too weak to support recovery. Hydrological thresholds occur when runoff dominates infiltration or soil moisture does not persist long enough for establishment.

A historical reference state assumes that the climate that produced it is still available (Harris *et al.*, 2006). In many drylands, rainfall amount, event intensity, dry-spell length, and evaporative demand have changed, so improved soil condition may not be enough to recover the former vegetation state (Wang *et al.*, 2012). SMRF therefore separates soil recovery

from endpoint feasibility. It asks whether infiltration and root-zone storage, surface stability, and propagule capture can recover under current and projected climate, and whether the historical target remains realistic. Soil memory and climate non-stationarity are treated as separate constraints.

Threshold status is expressed as reversible, conditionally reversible, or functionally irreversible under the stated restoration objective. The last category means that the intended endpoint requires redesign; it does not imply that no ecological or soil-function recovery is possible. Sites within a reversible range may respond to protection or assisted natural regeneration, whereas sites with confirmed soil or hydrological constraints may require targeted treatment before planting. Where the intended state is no longer feasible under current climate, soil, or management conditions, the target may shift toward defined functions or land-use redesign. Table 3 separates diagnostic indicators from warning signals and locally calibrated thresholds, while Figure 3 illustrates the three threshold states conceptually.

SMRF distinguishes diagnostic indicators, warning signals, and thresholds. A diagnostic indicator is a measured variable. A warning

Table 3. Diagnostic indicators, warning signals, and locally calibrated threshold interpretation in dryland restoration

Domain	Diagnostic indicator	Warning signal	Threshold interpretation	Restoration meaning	Supporting references
Chemical	SAR/ESP	Sodium hazard is elevated relative to soil texture, clay behavior, and electrolyte concentration	Warning signal; a decision threshold requires local calibration	Investigate dispersion, infiltration, drainage, and amendment feasibility before planting	(Sumner, 1993; Qadir <i>et al.</i> , 2007; Ogle and St. John, 2009; Daliakopoulos <i>et al.</i> , 2016; Corwin and Scudiero, 2019; Corwin, 2021; Hopmans <i>et al.</i> , 2021)
Chemical	ECe	Salinity approaches the tolerance range of the target vegetation or restricts germination	Species- and soil-specific; not a universal SMRF threshold	Assess root-zone salinity, drainage or leaching feasibility, and species tolerance	(Sumner, 1993; Qadir <i>et al.</i> , 2007; Ogle and St. John, 2009; Daliakopoulos <i>et al.</i> , 2016; Corwin and Scudiero, 2019; Corwin, 2021; Hopmans <i>et al.</i> , 2021)
Physical	Bulk density / penetration resistance	Root growth or profile exploration is measurably restricted	Threshold depends on texture, soil moisture at measurement, rooting depth, and target species	Confirm the limiting layer before physical treatment or broad seeding	(Hamza and Anderson, 2005; Batey, 2009; Nawaz <i>et al.</i> , 2013; Rabot <i>et al.</i> , 2018)
Physical	Crust strength / surface sealing	Crusting is associated with poor emergence or reduced infiltration	Warning signal; threshold requires a local relationship with emergence or infiltration response	Assess safe-site availability and whether surface treatment is required	(Valentin and Bresson, 1992; Hillel, 1998; Hamza and Anderson, 2005; Batey, 2009; Nawaz <i>et al.</i> , 2013; Rabot <i>et al.</i> , 2018)
Biological	Native seed bank / recruitment	Native propagule supply or recruitment is below an appropriate local reference	Reference-based warning; recruitment threshold requires local evidence	Assess seed-source limitation, dispersal, and safe-site availability before seed addition	(Kemp, 1989; Kinloch and Friedel, 2005; Chambers <i>et al.</i> , 2007)
Biological	BSC condition	BSC cover, continuity, or functional condition is below an appropriate local reference	Warning signal; recovery threshold depends on disturbance history and local surface conditions	Assess protection, surface stability, and BSC recovery potential before active treatment	(Eldridge and Greene, 1994; Belnap and Eldridge, 2003; Belnap, 2006; Bowker, 2007; Maestre <i>et al.</i> , 2011; Pointing and Belnap, 2012; Duniway <i>et al.</i> , 2019; Antoninka <i>et al.</i> , 2020)
Biological	Microbial / mycorrhizal indicators	Direct measurements show persistent disruption relative to an appropriate local reference	No universal threshold; interpretation is site- and method-specific	Consider microbial or mycorrhizal intervention only when the limitation is directly supported	(Requena <i>et al.</i> , 2001; Harris <i>et al.</i> , 2006; Kulmatiski <i>et al.</i> , 2008; Harris, 2009; Delgado-Baquerizo <i>et al.</i> , 2016; Hannula <i>et al.</i> , 2021)
Hydrological	Infiltration / runoff / soil-moisture persistence	Rainfall is lost mainly as runoff or root-zone moisture is too short-lived for establishment	Site-specific threshold linked to rainfall regime, surface condition, and landform	Diagnose runoff connectivity and water retention before hydrological treatment	(Wilcox <i>et al.</i> , 2003; Ludwig <i>et al.</i> , 2005; Turnbull <i>et al.</i> , 2008; Moreno-de las Heras <i>et al.</i> , 2010; D'Odorico <i>et al.</i> , 2012; Wang <i>et al.</i> , 2012; Mayor <i>et al.</i> , 2013)

Note: Diagnostic indicators are measured variables; warning signals identify conditions that require further investigation; thresholds require a locally supported relationship with restoration response. None of the warning signals listed here should be interpreted as a universal numerical threshold.

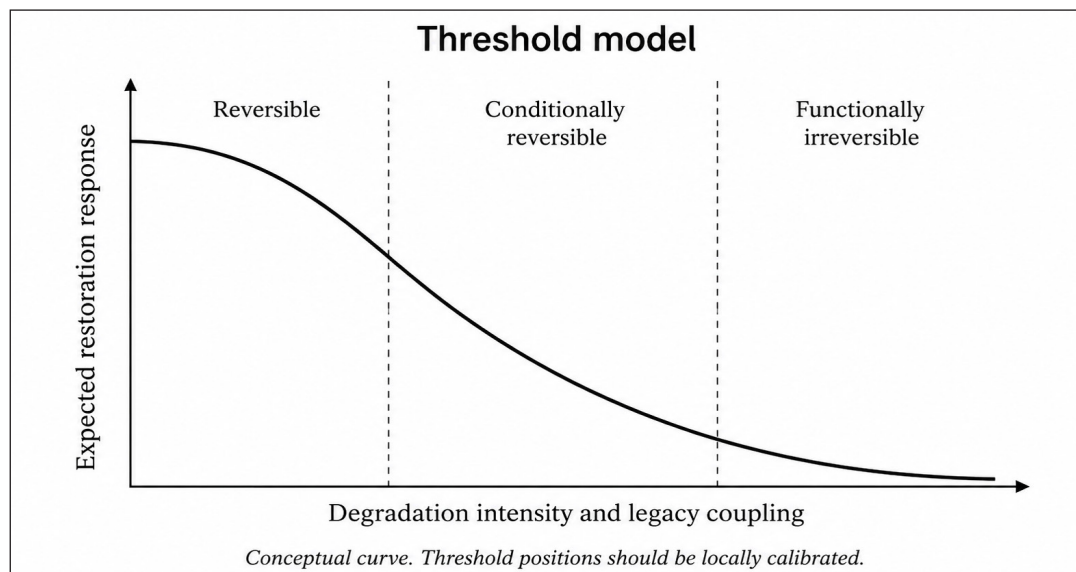


Fig. 3. Threshold model showing reversible, conditionally reversible, and functionally irreversible restoration states. The curve is conceptual and should be locally calibrated.

signal is an indicator or field observation that departs from an appropriate local reference and warrants further investigation. A threshold is a locally supported value, range, or transition associated with a material change in establishment, recovery, or ecosystem function. Accordingly, variables such as SAR, ESP, E_{Ce}, bulk density, penetration resistance, SOC, BSC condition, infiltration, and runoff response remain indicators unless their relationship with restoration response has been demonstrated for the relevant soil and ecological setting.

Restoration failure reinterpreted through soil memory: A soil-memory lens provides an additional way to investigate restoration failure. Failure may reflect a persistent soil constraint, a current implementation problem, or both. In SMRF, degradation-linked soil and surface legacies are evaluated separately from current grazing, access, tenure, enforcement, and maintenance. The former are classified as soil memory only when the historical-link and persistence criteria defined in Section 3 are met; the latter are recorded as feasibility conditions.

Five failure patterns are used in this review. Type I is immediate establishment failure during germination, emergence, or the first year after intervention. Type II is delayed decline after initial establishment. Type III is partial functional recovery, in which cover or biomass improves while composition, recruitment, or one or more supporting soil or hydrological functions remain incomplete. Type IV is

structural or geomorphic failure caused by active runoff, erosion, gully expansion, sand movement, burial, or failure of restoration structures. Type V is implementation or management failure, where recurrent grazing, access, weak protection, short project cycles, poor maintenance, or unresolved tenure undermines an otherwise plausible treatment.

These categories can occur together within one project. A site may show immediate failure in seeded microsites, structural failure along active flow paths, and implementation failure where grazing resumes after treatment. The typology should therefore be applied to functional units rather than to the whole project as a single label. It also shows why first-year survival or vegetation cover alone can miss delayed decline or incomplete functional recovery.

Table 4 sets out the five patterns against the evidence behind each and the diagnostic step it calls for.

The value of the typology is that each pattern leads to a different diagnostic question. Crusting requires assessment of the soil surface rather than simply more seed. Suspected subsoil sodicity requires root-zone measurements rather than surface fertilization. Apparent recovery requires checks on recruitment, composition, hydrology, and relevant soil functions. Structural failure requires runoff and erosion control. Implementation failure

Table 4. SMRF typology of restoration failure and the next diagnostic step

Failure type	Timing	Main signal	Illustrative evidence	Potential constraint to be investigated	Next diagnostic step	References
Type I: Immediate establishment failure	0–1 year	Poor germination, emergence, or early survival	Across 174 dryland seeding sites, 17% of projects established none of the seeded species	Seed or species mismatch; drought; grazing; chemical, physical, or hydrological constraint	Check seed and species factors together with soil-surface and root-zone conditions	(Sumner, 1993; Qadir <i>et al.</i> , 2007; Batey, 2009; Ogle and St. John, 2009; Daliakopoulos <i>et al.</i> , 2016; Corwin and Scudiero, 2019; Corwin, 2021; Shackelford <i>et al.</i> , 2021; Hopmans <i>et al.</i> , 2021; Copeland <i>et al.</i> , 2025; Sowards <i>et al.</i> , 2025)
Type II: Delayed decline	After initial establishment	Established plants decline with time	Seeded-species occurrence declined as projects matured	Root-zone chemistry or structure; limited rooting; poor moisture persistence; recurrent drought; maintenance	Extend monitoring and examine root-zone chemistry, structure, and moisture	(Hamza and Anderson, 2005; Qadir <i>et al.</i> , 2007; Batey, 2009; Nawaz <i>et al.</i> , 2013; Rabot <i>et al.</i> , 2018; Wang <i>et al.</i> , 2012; Shackelford <i>et al.</i> , 2021)
Type III: Partial functional recovery	Variable	Cover or biomass improves while composition, recruitment, or soil function remains incomplete	Twenty years of rest in Karoo rangelands restored grazing potential but not palatable plant diversity	Biological limitation or another unmeasured functional constraint	Measure recruitment, composition, propagule supply, and relevant soil functions	(Seymour <i>et al.</i> , 2010)
Type IV: Structural or geomorphic failure	Event-driven or ongoing	Erosion, burial, breaching, or expanding runoff pathways	Post-fire studies report strong runoff and erosion responses under high bare-ground and slope conditions	Active runoff, erosion, gully expansion, sand movement, or connected bare ground	Diagnose flow and sediment pathways before stabilization or planting	(Moreno-de las Heras <i>et al.</i> , 2010; Pierson <i>et al.</i> , 2015)
Type V: Implementation failure	Variable	Treatment is undermined by recurrent disturbance or weak maintenance	No universal quantitative threshold applies	Grazing, access, tenure, enforcement, or maintenance	Record the feasibility constraint and reassess the technical pathway	(Gann <i>et al.</i> , 2019)

Note: Published examples illustrate failure patterns; they do not establish a soil-memory cause without site-specific diagnosis.

requires action on access, grazing, tenure, or maintenance. SMRF uses these distinctions to link the observed failure pattern to the next measurement and decision.

Soil Memory-Based Restoration Framework: The Soil Memory-Based Restoration Framework (SMRF) translates the soil-memory concept into a diagnosis-led sequence for dryland restoration. It begins with the restoration objective and then

asks which persistent soil or surface conditions are limiting recovery, whether those conditions are likely to restrict the intended restoration pathway, and which constraint should be addressed first. The starting point is therefore the cause of the limitation rather than the treatment itself.

Existing soil assessments provide essential information on current chemical, physical,

and biological condition, while restoration planning identifies desired states and possible management actions. SMRF connects these elements through a temporal diagnostic step: it asks whether a present constraint carries a persistent effect of past degradation and whether that effect is relevant to the intended restoration response. This helps explain why sites that appear similar above ground, or that have similar values for a single soil indicator, may respond differently when their degradation histories, root-zone conditions, hydrological behavior, or interacting constraints differ.

The practical value of this diagnosis appears at three decision points. Functional thresholds are interpreted against a defined restoration objective and local evidence rather than as universal cut-offs. Constraints that may prevent recovery are identified before intervention, allowing chemical, physical, biological, and hydrological limitations to be treated according to the process involved. Where several constraints interact, treatment is sequenced according to causal dependency: runoff or erosion may need to be controlled before planting, a limiting root-zone condition may need to be corrected before seeding, and biological recovery may depend on suitable water, rooting conditions, and propagule availability. Monitoring then follows the same logic by measuring the functions expected to respond to each intervention.

The seven SMRF rules were derived from recurring decision points identified across the evidence synthesis; they were not generated by statistical optimization, formal expert elicitation, or a validated scoring model. R1–R4 represent chemical, physical, hydrological, and biological constraint classes for which the reviewed literature repeatedly links measured site conditions with restoration response. R5 addresses active structural or geomorphic processes that can override establishment treatments. R6 addresses coupled constraints where treatment order depends on causal dependency, and R7 addresses management or climatic conditions that make the intended endpoint infeasible. The rules should therefore be read as synthesis-based screening and sequencing rules that require local testing, not as universally validated prescriptions. Supplementary Table S6 records the evidence basis and calibration requirement for each rule.

R1. Chemical-first. Where salinity or sodicity is suspected, EC_e, ESP and SAR are the screening indicators, read against local soil texture, electrolyte concentration, species tolerance and drainage rather than against a fixed cut-off. Where chemical constraints are evident, drainage, leaching, or amendment feasibility should be assessed before seeding (Sumner, 1993; Qadir *et al.*, 2007; Daliakopoulos *et al.*, 2016; Corwin and Scudiero, 2019; Corwin, 2021; Hopmans *et al.*, 2021).

R2. Physical-first. Trigger this pathway when penetration resistance, crusting, or another physical constraint clearly limits rooting or emergence under local soil and moisture conditions. Create safe sites or relieve the limiting physical condition before broad seeding (Hamza and Anderson, 2005; Batey, 2009; Nawaz *et al.*, 2013; Rabot *et al.*, 2018).

R3. Hydrology-first. Trigger this pathway when field measurements show that rainfall is being lost mainly as runoff or that soil moisture does not persist long enough for establishment. Stabilize or redistribute runoff before planting (Wilcox *et al.*, 2003; Ludwig *et al.*, 2005; Turnbull *et al.*, 2008; Moreno-de las Heras *et al.*, 2010; D’Odorico *et al.*, 2012; Wang *et al.*, 2012; Mayor *et al.*, 2013).

R4. Biological constraint-specific pathway. Use this pathway only after the biological bottleneck has been identified. Propagule limitation should be assessed through native seed-bank, seed-source, or recruitment evidence (Kemp, 1989; Kinloch and Friedel, 2005; Chambers *et al.*, 2007); microbial or mycorrhizal limitation requires direct biological evidence (Requena *et al.*, 2001; Belnap and Phillips, 2001; Harris *et al.*, 2006; Kulmatiski *et al.*, 2008; Harris, 2009; Ehrenfeld, 2010; Perkins and Nowak, 2013; Delgado-Baquerizo *et al.*, 2016; Hannula *et al.*, 2021; Peddle *et al.*, 2025); biological soil-crust degradation requires assessment of BSC condition, surface stability, and recovery potential (Eldridge and Greene, 1994; Belnap and Eldridge, 2003; Belnap, 2006; Bowker, 2007; Maestre *et al.*, 2011; Pointing and Belnap, 2012; Duniway *et al.*, 2019; Antoninka *et al.*, 2020); and organic-matter limitation should be assigned only where degradation-linked loss is supported relative to an appropriate reference. The intervention should match the

confirmed biological constraint rather than a generic biological treatment.

R5. Stabilize before planting. Assess bare ground, slope, runoff connectivity, and active erosion together when evaluating structural risk. The combination of 50–60% bare ground and slopes above 15% is retained only as a published post-fire rangeland reference point and should not be treated as a universal threshold (Pierson *et al.*, 2015).

R6. Sequenced package. Where two or more constraints are active, order treatments according to causal dependency and the dominant site-specific bottleneck rather than a fixed domain hierarchy. Acute runoff or erosion hazards should be stabilized first where present; other chemical, physical, and biological constraints should then be treated in the order indicated by field evidence.

R7. Land-use redesign. Consider redesign where the required management conditions cannot be maintained or where the intended recovery state is no longer feasible under current and projected climate.

Supplementary Table S6 records the evidence basis and calibration status of each screening rule. Figure 4 gives the same logic as a decision algorithm. Table 5 gives the stage-by-stage protocol, with the minimum output required at each stage.

Where none of these conditions is evident, passive recovery with monitoring is the first option.

The sequence is not fixed and the rule numbers do not represent a universal treatment hierarchy. Chemical, physical, hydrological, biological, structural, coupled, and feasibility constraints are evaluated within the same site-specific diagnosis. Constraints that may prevent establishment are examined early where field evidence indicates that they are active, and treatment order is then determined by causal dependency and the dominant bottleneck within each functional unit.

Screening values are not transferable between soil types, because the process they index is not the same. On a dispersive sodic surface, a small increase in exposed area can be enough

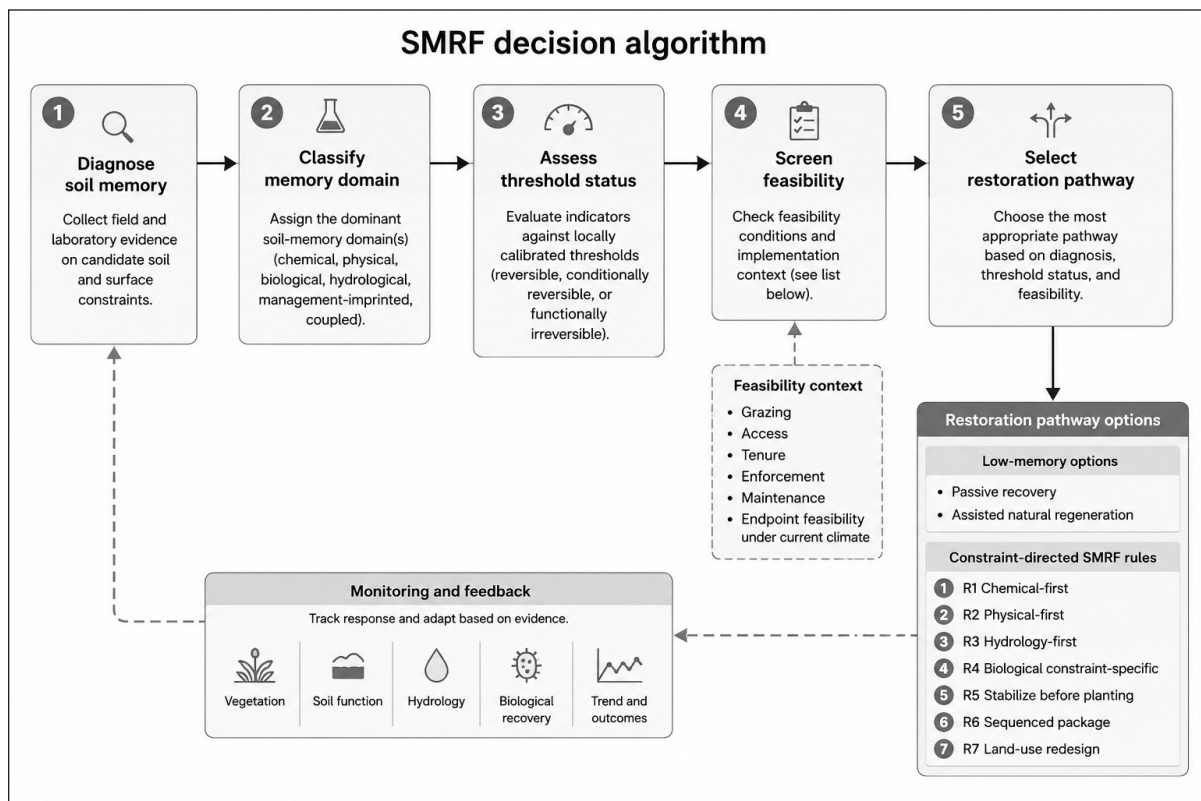


Fig. 4. SMRF decision algorithm. Restoration pathways are selected after diagnosis, memory-domain classification, threshold assessment, and feasibility screening.

Table 5. Operational sequence for applying SMRF

Stage	Core action	Minimum output	Decision use
1. Problem framing	Define the objective and acceptable future state	Target functions	Sets the basis for interpretation
2. Functional-unit delineation	Divide the site into coherent soil-landform units	Unit map	Prevents whole-site classification
3. Memory assignment	Assess whether each candidate constraint meets the historical-link and persistence criteria	Memory class, evidence basis, and confidence note	Separates assigned soil memory from constraints that still require confirmation
4. Threshold assessment	Separate indicators, warning signals, and locally supported thresholds	Threshold-status record	Defines reversibility and uncertainty
5. Feasibility screening	Assess current management and climate-related endpoint feasibility	Feasibility record	Tests whether the pathway can be sustained
6. Pathway selection	Match treatment to the confirmed limiting process	Ordered intervention sequence	Guides treatment choice
7. Monitoring	Track indicators linked to the expected response and failure mode	Monitoring plan	Tests whether targeted functions recover

to seal the profile. On a coarse hyper-arid surface, bare ground is the normal condition and the relevant variable is the connectivity of the bare area rather than its extent. Applying one value across both repeats the error that made earlier universal restoration guidelines unusable. Local recalibration is a requirement of the framework, not a caveat on it.

Intervention intensity is guided by the type, severity, and interaction of the active constraints rather than by visible degradation alone. Adequate soil function and propagule supply may support protection or assisted natural regeneration; a confirmed soil or hydrological bottleneck points to treatment of that constraint first; and an unattainable endpoint points to land-use redesign. Each pathway is therefore linked to measured limiting processes.

Geospatial and diagnostic measurement of soil memory: Remote sensing adds an essential spatial layer, but it should not be treated as proof of restoration success on its own. Earlier restoration assessments often used remote sensing mainly as a screening tool. Indices such as the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), soil-adjusted vegetation index (SAVI), fractional vegetation cover, bare soil index, albedo, and land surface temperature can identify spatial patterns and help prioritize field assessment (Tucker, 1979; Metternicht and Zinck, 2003; Washington-Allen *et al.*, 2006; Právělie, 2016; Corwin and Scudiero, 2019). Yet greening alone cannot distinguish native recovery from invasive dominance, ephemeral growth after

rainfall, irrigation leakage, fertilization effects (Li *et al.*, 2025), or genuine recovery of soil function. Remote sensing therefore stratifies the sampling design. Recovery claims rest on the field and laboratory measurements of soil function collected within those strata.

The division between remote and field measurement should be explicit. Imagery can detect vegetation trajectories, bare-ground patterns, surface brightness, some erosion features, sand movement, and surface salt expression. Subsurface EC_e, ESP and SAR, bulk density, penetration resistance, effective rooting depth, SOC, germinable seed-bank density, and microbial or mycorrhizal function require field or laboratory confirmation. Remote sensing should therefore be used to screen and stratify the landscape; it should not assign a soil-memory class or trigger R1–R4 without ground data. Figure 5 shows the division of work between the geospatial and the field layers.

A robust application of the Soil Memory-Based Restoration Framework should therefore be geospatially explicit. Google Earth Engine can be used to assemble long-term image stacks from Landsat, Sentinel-2, digital elevation models (DEMs), soil-moisture products, bare-soil layers, and climate grids (Gorelick *et al.*, 2017). R and Python can then support trend testing, breakpoint detection, seasonal decomposition, spatial stratification, machine-learning classification, uncertainty mapping, and model validation. Algorithms such as LandTrendr (Kennedy *et al.*, 2018), continuous

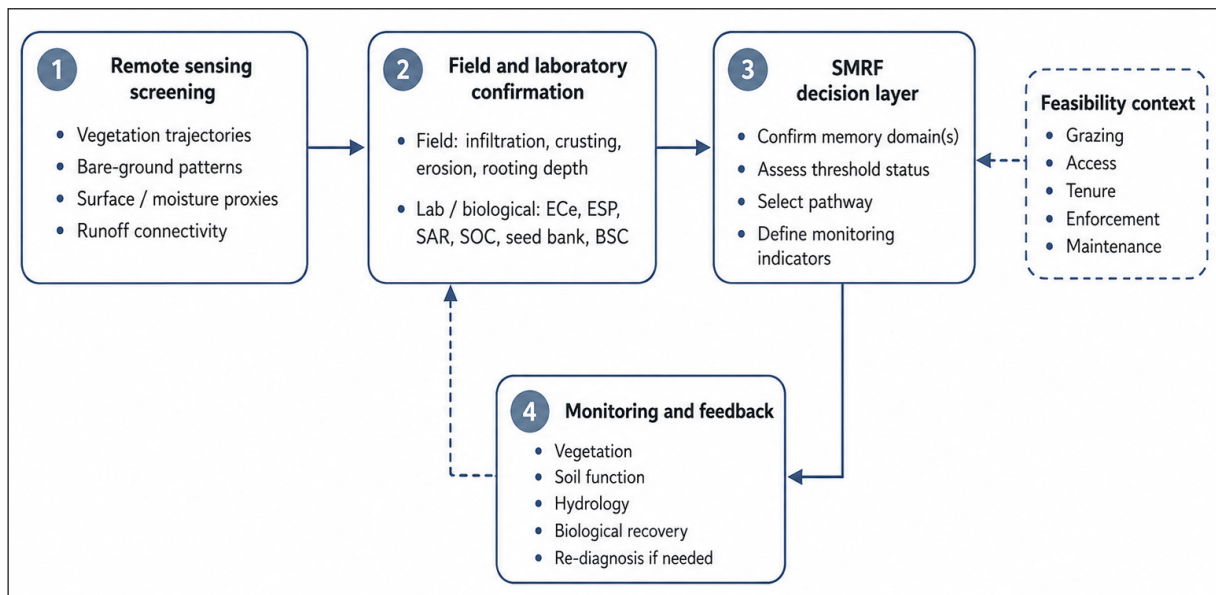


Fig. 5. Geospatial implementation of SMRF. Remote sensing is used for screening and stratification, while soil-memory classification requires field or laboratory confirmation. Feasibility conditions are recorded separately.

change detection (Zhu and Woodcock, 2014), and seasonal-trend decomposition (Verbesselt *et al.*, 2010) can help detect persistent greening, browning, disturbance, and recovery signals, but these signals remain incomplete unless calibrated against soil-memory indicators measured on the ground (Bernardino *et al.*, 2025).

The output is a screening surface or priority map for field verification, not a probabilistic risk map or a direct map of soil memory. It identifies locations where remote observations are consistent with conditions that warrant field investigation. A practical workflow begins by using remote sensing to stratify the landscape and prioritize sampling, followed by soil, vegetation, and hydrological measurements within those strata. Field and laboratory evidence is then used to assign soil-memory classes, interpret threshold status, and select restoration pathways.

Supplementary Table S3 lists the data sources, tools and calibration requirements for each layer of this workflow.

Cross-regional dryland contexts and transferable soil-memory lessons: The Soil Memory-Based Restoration Framework can be applied across drylands only after local calibration. Hyper-arid systems may combine low organic inputs, salinity, alkalinity, and episodic runoff (Sumner, 1993; Rengasamy, 2006; Qadir *et al.*, 2007; Daliakopoulos *et al.*,

2016; Corwin and Scudiero, 2019; Corwin, 2021; Hopmans *et al.*, 2021), while semi-arid rangelands may retain compaction, crusting, biological-soil-crust damage, and propagule loss after long disturbance histories (Thurrow, 1991; Valentin and Bresson, 1992; Eldridge and Greene, 1994; Hillel, 1998; Breshears *et al.*, 2003; Belnap and Eldridge, 2003; Hamza and Anderson, 2005; Kinloch and Friedel, 2005; Bowker, 2007; Chambers *et al.*, 2007; Batey, 2009; Ravi *et al.*, 2010; Nawaz *et al.*, 2013; Webb *et al.*, 2014; Rabot *et al.*, 2018; Duniway *et al.*, 2019; Kushbokov *et al.*, 2025). Rain-fed farming margins can retain topsoil loss, nutrient depletion, and low SOC after cultivation ceases (García *et al.*, 1997; Lal, 2001; Bastida *et al.*, 2015). Terraced and hillslope systems can remain limited by runoff concentration, sediment redistribution, shallow soil depth, and structural instability (Wilcox *et al.*, 2003; Ludwig *et al.*, 2005; Bautista *et al.*, 2007; Moreno-de las Heras *et al.*, 2010; Cortina *et al.*, 2011; D'Odorico *et al.*, 2012; Mayor *et al.*, 2013; Al-Ghamdi *et al.*, 2021). These differences are why SMRF uses local diagnosis rather than dryland category alone to select a pathway.

Mobile and semi-mobile sand systems show why surface condition and propagule processes need to be diagnosed separately. Studies from Saudi inland sand systems describe vegetation structure after long protection and strong shrub effects on germinable seed-bank density and

richness (El-Sheikh *et al.*, 2021; Gomaa *et al.*, 2023). These studies do not test a complete restoration package, but they show that sand mobility, shrub microsites, seed retention, and rainfall can shape recruitment. Under SMRF, broad revegetation would therefore follow assessment of surface stability, rooting conditions, propagule availability, and moisture persistence.

Hillslope and restored dryland systems provide another coupled case. Evidence from southwestern Saudi Arabia shows that restored and comparison sites can differ in soil physicochemical condition (Al-Ghamdi *et al.*, 2021; Ezzat *et al.*, 2025), while Mediterranean hillslope studies link vegetation pattern and surface condition to runoff and sediment loss (Bautista *et al.*, 2007; Cortina *et al.*, 2011). Under SMRF, these observations justify checking runoff concentration, structural stability, effective soil depth, and moisture retention before planting. Structural repair should be selected only where field evidence shows that these processes limit establishment.

Illustrative application: Karoo rangeland exclosure, South Africa: The long-term Karoo exclosure is used here as an illustrative application of SMRF rather than as a validation test. After 20 years of rest, grazing potential

had recovered, but palatable plant diversity had not (Seymour *et al.*, 2010). Within SMRF, this outcome would be treated as Type III partial functional recovery and would trigger further diagnosis rather than assignment of a biological cause. Propagule availability, recruitment, soil-surface condition, and relevant biological indicators would be assessed together with physical and hydrological constraints. A biological treatment would be considered only if a specific biological limitation were confirmed. The example therefore shows how SMRF can organize the next diagnostic steps without attributing an unmeasured mechanism to the original study. Figure 6 places this example within a broader set of dryland contexts in which different constraints may lead to different restoration pathways.

The Loess Plateau provides a contrasting example of the limits of retrospective interpretation. Vegetation cover increased and erosion declined during a period in which rainfall patterns and large engineering interventions also changed, and their relative contributions remain difficult to separate (Fu *et al.*, 2011; Zhang *et al.*, 2016). A greening signal therefore cannot be interpreted as evidence of recovered soil function when climate and restoration measures are changing at the same

1. Inland sand seas	2. Terraced uplands	3. Saline-sodic margins	4. Overgrazed rangelands
			
 Dominant soil memory: Physical + biological	 Dominant soil memory: Hydrological + physical	 Dominant soil memory: Chemical + hydrological	 Dominant soil memory: Physical + biological + management-imprinted
 Main diagnostic focus: Sand mobility, safe sites, propagule availability, moisture persistence	 Main diagnostic focus: Runoff concentration, structural stability, soil depth, moisture retention	 Main diagnostic focus: ECe, ESP, SAR, drainage, leaching feasibility	 Main diagnostic focus: Ground cover, infiltration, species composition, current grazing pressure
 Priority pathway: Stabilize active surface before broad revegetation	 Priority pathway: Repair runoff and structural constraints before planting	 Priority pathway: Treat chemical constraint and drainage before reseeding	 Priority pathway: Protect where recovery capacity remains; treat persistent soil legacies as needed
 Monitoring focus: Surface stability, recruitment, moisture persistence	 Monitoring focus: Runoff, erosion, soil depth, vegetation recovery	 Monitoring focus: ECe, ESP, SAR, infiltration, vegetation response	 Monitoring focus: Ground cover, infiltration, species composition
 SMRF implication: Threshold status must be determined locally. Restoration pathways should be calibrated to dominant soil memory, threshold status, and management context.			

Fig. 6. Representative dryland contexts for applying SMRF. Inland sand seas, terraced uplands, saline-sodic margins, and overgrazed rangelands illustrate why restoration pathways should be calibrated to local soil-memory evidence, threshold status, and management context.

Table 6. Condensed cross-regional evidence matrix linking soil memory to dryland restoration outcomes

Region/ system	Evidence reported in cited source(s)	Soil-memory interpretation in this review	SMRF implication	Reference(s)
Global dryland seeding projects	Across 174 sites on six continents, 17% of projects had no establishment of any seeded species, and seeded-species occurrence declined as projects matured	Restoration response varies with site conditions as well as seed traits and seeding rate; failure alone does not identify a soil cause	Diagnose site and soil constraints before repeated seeding and monitor beyond initial establishment	(Shackelford <i>et al.</i> , 2021)
US Southwest and Great Basin degradation contexts	Annual-grass invasion altered soil biota, while sandy shrubland degradation involved loss and redistribution of soil resources	Biological and physical legacies can interact with vegetation change	Assess invasion legacy, soil-surface stability, and erosion before assigning a seeding response	(Belnap and Phillips, 2001; Okin <i>et al.</i> , 2001)
Sahel agro- pastoral systems	Farmer-led soil and water conservation and natural regeneration rehabilitated degraded land, while regional evidence shows effects of land management on woody cover	Hydrological processes and current management can jointly affect recovery	Diagnose hydrological constraints and treat current management as a separate feasibility condition	(Reij <i>et al.</i> , 2009; Brandt <i>et al.</i> , 2018)
Karoo rangelands, South Africa	Twenty years of rest restored grazing potential but not palatable plant diversity	Partial recovery does not identify the remaining biological mechanism without direct measurement	Measure recruitment, composition, and biological indicators before assigning a biological constraint-specific pathway	(Seymour <i>et al.</i> , 2010)
Saudi inland sand systems	Protected nafud vegetation retained diverse plant associations, and <i>Haloxylon persicum</i> shrubs increased germinable seed-bank density and richness beneath their canopies	Aeolian surface condition and shrub microsites can influence propagule retention and recruitment	Assess sand stability, safe-site structure, seed availability, and moisture before broad revegetation	(El-Sheikh <i>et al.</i> , 2021; Gomaa <i>et al.</i> , 2023)
Southwestern Saudi restored sites	Restored and comparison areas showed variable soil physicochemical responses	Restoration response can differ with underlying chemical and physical soil condition	Use baseline soil properties to stratify sites and interpret vegetation response	(Al-Ghamdi <i>et al.</i> , 2021)
Iberian semiarid hillslopes	Vegetation spatial pattern and surface condition were linked to runoff and sediment loss, while regional restoration studies report variable constraints and objectives	Hydrological and physical structure can shape recovery	Diagnose runoff connectivity, soil-surface condition, and microsites before intervention	(Bautista <i>et al.</i> , 2007; Cortina <i>et al.</i> , 2011)
Loess Plateau, China	Large restoration programs were associated with increased vegetation cover and improved erosion control, with climate and engineering measures also contributing	Hydrological and physical processes interact with vegetation recovery at landscape scale	Interpret greening together with runoff, erosion, and climate trends	(Fu <i>et al.</i> , 2011; Zhang <i>et al.</i> , 2016)
Australian semiarid landscapes	Rehabilitation and ecohydrological studies emphasize productive soil patches and vegetation-runoff-erosion feedbacks	Physical and hydrological patch structure controls resource retention and redistribution	Diagnose patch connectivity and runoff redistribution before selecting soil or hydrological treatment	(Tongway and Ludwig, 1996; Ludwig <i>et al.</i> , 2005)
Biological soil-crust restoration studies	BSC literature documents active protection and inoculation approaches together with limitations to field recovery	Biological surface recovery may require direct treatment where natural recovery is slow	Measure BSC condition directly rather than infer recovery from vegetation cover	(Bowker, 2007; Antoninka <i>et al.</i> , 2020; Jech <i>et al.</i> , 2025)

time. The same caution applies to SMRF: where soil-memory indicators and climatic trends point in the same direction, attribution requires a study design capable of separating their effects.

Together, these examples show why global restoration targets should not be translated directly into local treatment prescriptions. Land Degradation Neutrality and other large-scale programs need to distinguish the area treated or vegetation cover gained from the recovery of soil function (Cowie *et al.*, 2018; UNCCD, 2022). Soil-memory assessment can help identify where passive recovery is realistic, where additional treatment is required, and where a functional target or alternative land-use state is more appropriate than attempting to recreate a past ecosystem condition.

Cross-regional evidence matrix linking soil memory to restoration outcomes: Table 6 gives a condensed evidence-tracing matrix. Supplementary Table S5 provides the expanded version, separating what each cited source reports from the soil-memory interpretation made in this review. The matrix is qualitative and is not used to estimate effect sizes, treatment success rates, or the frequency of particular memory domains.

Policy and management implications

A soil-memory diagnosis may improve restoration planning by identifying persistent constraints before intervention. In drylands, baseline assessment of relevant soil and hydrological processes can help determine whether planting, protection, soil treatment, or hydrological intervention is appropriate. Where persistent constraints are suspected, project budgets may need to include targeted diagnosis, site protection, maintenance, and longer-term monitoring rather than concentrating mainly on planting inputs.

Monitoring should pair vegetation response with the functions linked to the diagnosed constraint, including infiltration, SOC, native recruitment, and runoff where relevant. Where vegetation cover improves while one or more of these functions remain incomplete, the outcome is classified as Type III partial functional recovery. This distinction allows monitoring to separate visible improvement from recovery of the functions targeted by

the intervention. Land degradation neutrality accounting should likewise distinguish avoided degradation, partial functional recovery, and recovery of soil function (UNCCD, 2017; Cowie *et al.*, 2018; UNCCD, 2022).

A soil-memory perspective can broaden restoration targets beyond area treated to include the functions intended for recovery. Depending on the diagnosed constraint, this may support protection, chemical or physical soil treatment, hydrological intervention, a constraint-specific biological treatment, or a revised functional target where the former ecosystem state is no longer feasible. Reporting can then pair hectares treated and survival counts with the pre-treatment diagnosis and post-treatment measurements of the functions targeted by the intervention.

Reporting should use the same functional soil-landform units used for SMRF classification and should state the unit boundaries, evidence basis, threshold status, intervention sequence, monitoring duration, and observed outcome. This prevents heterogeneous restoration sites from being summarized as a single soil-memory class.

Knowledge gaps and future research agenda

Several knowledge gaps still limit the operational use of soil memory in dryland restoration. The most important gap is the absence of a standardized diagnostic vocabulary that connects inherited soil constraints with restoration outcomes. Many studies describe salinity, sodicity, compaction, crusting, BSC disturbance, seed-bank depletion, or altered hydrology, but these indicators are rarely interpreted together as interacting memory domains that shape recovery.

A second gap concerns measurement. Restoration studies often track vegetation more consistently than the soil, hydrological, and biological functions expected to sustain it. Longer process-based monitoring is therefore needed to determine whether observed recovery persists and whether the functions targeted by the intervention have recovered.

A third gap concerns thresholds and time scale. Locally calibrated ranges for chemical, physical, biological, and hydrological indicators remain limited across many dryland soils and vegetation types. Implementation conditions

also vary among projects, which limits how far any single calibration transfers. Short monitoring periods make delayed failure harder to detect where drought recurrence, episodic recruitment, and slow belowground recovery shape long-term outcomes.

The framework is testable, although existing datasets were not assembled for this purpose. If soil memory contributes independently to establishment, pre-treatment soil condition should explain part of the remaining variation after major factors such as seeding rate, seed mass, aridity, and species identity are accounted for. Testing this requires soil chemical and physical measurements recorded at the time of intervention. Adding a minimum pre-treatment soil panel to restoration reporting would therefore provide an important basis for testing SMRF across sites.

Supplementary Table S4 sets out each gap against the study design that would close it.

Scope and limitations

No universal numerical rule is offered, because none is currently defensible: soil-memory thresholds are not standardized across textures and aridity levels (Abel *et al.*, 2024). No indicator used within the Soil Memory-Based Restoration Framework carries a fixed meaning across soil textures and aridity levels; each trigger value is an entry point for local calibration rather than a fixed global threshold.

A second limitation is geographic and empirical validation. The evidence base is uneven across dryland regions, and SMRF has not yet been prospectively tested as a complete decision framework in independent field trials. Evidence from Arabian, African, Australian, Mediterranean, Chinese, and North American systems informs parts of the framework, but this is not the same as validating the full sequence. Indicators, local reference conditions, and pathway rules should therefore be calibrated and tested before operational use in a new region.

A third limitation concerns evidence organization. This review uses structured evidence synthesis to connect concepts across disciplines, but it does not claim to provide a formal bibliometric analysis, citation network, or quantitative literature map. Future studies could extend this work through fully

reproducible bibliometric analysis using exported database records, transparent keyword harmonization, documented software settings, and supplementary network files.

Conclusion

Dryland restoration failure cannot be explained only by planting, maintenance, or species choice. Persistent soil legacies can continue to restrict infiltration, rooting, recruitment, water retention, and surface stability after the original pressure declines. SMRF provides a diagnosis-led sequence that links memory domains, locally calibrated threshold status, feasibility screening, pathway selection, and monitoring of soil, hydrological, biological, and vegetation recovery.

The framework does not replace vegetation monitoring or remote sensing. It places them within a process-based diagnosis in which remote observations identify change and ground measurements determine whether function has recovered. Large-scale restoration programs should therefore report area treated and vegetation response together with evidence of restored soil and hydrological function. Treatments are selected after limiting processes are identified, and success is judged by persistence of the targeted functions through climatic variability.

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The authors declare no competing financial or non-financial interests.

Data availability

No new data were generated or analyzed in this review. All sources used in the evidence synthesis are cited in the manuscript and listed in the References.

Author contributions

Jamal Elfaki and Mushtaha Ali contributed to the conceptualization of the review, literature synthesis, development of the Soil Memory-Based Restoration Framework, interpretation of the evidence, and preparation and revision of the manuscript. Both authors reviewed and approved the final manuscript.

References

- Abel, C., Maestre, F.T., Berdugo, M., Tagesson, T., Abdi, A.M., Horion, S. and Fensholt, R. 2024. Vegetation resistance to increasing aridity when crossing thresholds depends on local environmental conditions in global drylands. *Communications Earth & Environment* 5: 379. doi:10.1038/s43247-024-01546-w
- Al-Ghamdi, A.A., Tadesse, Y., Adgaba, N. and Alghamdi, A.G. 2021. Soil degradation and restoration in southwestern Saudi Arabia through investigation of soil physiochemical characteristics and nutrient status as indicators. *Sustainability* 13(16): 9169. doi:10.3390/su13169169
- Antoninka, A., Faist, A., Rodriguez-Caballero, E., Young, K.E., Chaudhary, V.B., Condon, L.A. and Pyke, D.A. 2020. Biological soil crusts in ecological restoration: Emerging research and perspectives. *Restoration Ecology* 28(S2): S3-S8.
- Aronson, J. and Alexander, S. 2013. Ecosystem restoration is now a global priority: Time to roll up our sleeves. *Restoration Ecology* 21(3): 293-296.
- Austin, A.T. 2011. Has water limited our imagination for aridland biogeochemistry? *Trends in Ecology & Evolution* 26(5): 229-235.
- Bastida, F., Selevsek, N., Torres, I.F., Hernández, T. and García, C. 2015. Soil restoration with organic amendments: Linking cellular functionality and ecosystem processes. *Scientific Reports* 5: 15550.
- Batey, T. 2009. Soil compaction and soil management: A review. *Soil Use and Management* 25(4): 335-345.
- Bautista, S., Mayor, A.G., Bourakhouadar, J. and Bellot, J. 2007. Plant spatial pattern predicts hillslope runoff and erosion in a semiarid Mediterranean landscape. *Ecosystems* 10(6): 987-998.
- Belnap, J. 2003. The world at your feet: Desert biological soil crusts. *Frontiers in Ecology and the Environment* 1(4): 181-189.
- Belnap, J. 2006. The potential roles of biological soil crusts in dryland hydrologic cycles. *Hydrological Processes* 20(15): 3159-3178.
- Belnap, J. and Eldridge, D.J. 2003. Disturbance and recovery of biological soil crusts. In: *Biological Soil Crusts: Structure, Function, and Management* (Eds. J. Belnap and O.L. Lange), pp. 363-383. Springer.
- Belnap, J. and Phillips, S.L. 2001. Soil biota in an ungrazed grassland: Response to annual grass invasion. *Ecological Applications* 11(5): 1261-1275.
- Bernardino, P.N., De Keersmaecker, W., Horion, S., Oehmcke, S., Gieseke, F., Fensholt, R., Van De Kerchove, R., Lhermitte, S., Abel, C., Van Meerbeek, K., Verbesselt, J. and Somers, B. 2025. Predictability of abrupt shifts in dryland ecosystem functioning. *Nature Climate Change* 15: 86-91. doi:10.1038/s41558-024-02201-0
- Bestelmeyer, B.T., Okin, G.S., Duniway, M.C., Archer, S.R., Sayre, N.F., Williamson, J.C. and Herrick, J.E. 2015. Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment* 13(1): 28-36.
- Bowker, M.A. 2007. Biological soil crust rehabilitation in theory and practice: An underexploited opportunity. *Restoration Ecology* 15(1): 13-23.
- Brandt, M., Rasmussen, K., Hiernaux, P., Herrmann, S., Tucker, C.J., Tong, X., Tian, F., Mertz, O., Kergoat, L., Mbow, C., David, J.L., Melocik, K.A., Dendoncker, M., Vincke, C. and Fensholt, R. 2018. Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. *Nature Geoscience* 11: 328-333.
- Breshears, D.D., Whicker, J.J., Johansen, M.P. and Pinder, J.E. 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems. *Journal of Arid Environments* 55(1): 111-127.
- Briske, D.D., Bestelmeyer, B.T., Stringham, T.K. and Shaver, P.L. 2008. Recommendations for development of resilience-based state-and-transition models. *Rangeland Ecology & Management* 61(4): 359-367.
- Briske, D.D., Fuhlendorf, S.D. and Smeins, F.E. 2005. State-and-transition models, thresholds, and rangeland health: A synthesis of ecological concepts and perspectives. *Rangeland Ecology & Management* 58(1): 1-10.
- Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R. and Brussaard, L. 2018. Soil quality: A critical review. *Soil Biology and Biochemistry* 120: 105-125.
- Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E. and Whittaker, A. 2007. What makes Great Basin sagebrush ecosystems invulnerable by *Bromus tectorum*? *Ecological Monographs* 77(1): 117-145.
- Coban, O., De Deyn, G.B. and van der Ploeg, M. 2022. Soil microbiota as game-changers in restoration of degraded lands. *Science* 375(6584): abe0725.
- Copeland, S.M., Baughman, O.W., Bradford, J.B., Hardegree, S.P., Larson, J.E., Schlaepfer, D.R. and Badik, K.J. 2025. Managing to survive despite the weather: Seeding decisions affecting

- simulated dryland restoration outcomes. *Restoration Ecology* 33(6): e14362.
doi:10.1111/rec.14362
- Corbin, J.D. 2025. The influence of exotic species' legacies on pathways of restoration. *Restoration Ecology* 33(3): e14381.
doi:10.1111/rec.14381
- Cortina, J., Amat, B., Castillo, V., Fuentes, D., Maestre, F.T., Padilla, F.M. and Rojo, L. 2011. The restoration of vegetation cover in the semi-arid Iberian southeast. *Journal of Arid Environments* 75(12): 1377-1384.
doi:10.1016/j.jaridenv.2011.08.003
- Corwin, D.L. 2021. Climate change impacts on soil salinity in agricultural areas. *European Journal of Soil Science* 72(2): 842-862.
- Corwin, D.L. and Scudiero, E. 2019. Review of soil salinity assessment for agriculture across multiple scales using proximal and/or remote sensors. *Advances in Agronomy* 158: 1-130.
doi:10.1016/bs.agron.2019.07.001
- Cowie, A.L., Orr, B.J., Castillo Sanchez, V.M., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S. and Welton, S. 2018. Land in balance: The scientific conceptual framework for land degradation neutrality. *Environmental Science & Policy* 79: 25-35.
- Cramer, V.A., Hobbs, R.J. and Standish, R.J. 2008. What's new about old fields? Land abandonment and ecosystem assembly. *Trends in Ecology & Evolution* 23(2): 104-112.
- Cross, A.F. and Schlesinger, W.H. 1999. Plant regulation of soil nutrient distribution in the northern Chihuahuan Desert. *Plant Ecology* 145(1): 11-25.
- Daba, A.W. 2025. Rehabilitation of soil salinity and sodicity using diverse amendments and plants: A critical review. *Discover Environment* 3: 53.
doi:10.1007/s44274-025-00199-6
- Daily, G.C. 1995. Restoring value to the world's degraded lands. *Science* 269(5222): 350-354.
- Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P. and Ritsema, C.J. 2016. The threat of soil salinity: A European scale review. *Science of the Total Environment* 573: 727-739.
- Delgado-Baquerizo, M., Maestre, F.T., Reich, P.B., Jeffries, T.C., Gaitan, J.J., Encinar, D., Berdugo, M., Campbell, C.D. and Singh, B.K. 2016. Microbial diversity drives multifunctionality in terrestrial ecosystems. *Nature Communications* 7: 10541.
doi:10.1038/ncomms10541
- Demo, A.H., Gameda, M.K., Abdo, D.R., Guluma, T.N. and Adugna, D.B. 2025. Impact of soil salinity, sodicity, and irrigation water salinity on crop production and coping mechanism in areas of dryland farming. *Agrosystems, Geosciences & Environment* 8(1): e70072.
doi:10.1002/agg2.70072
- D'Odorico, P., Bhattachan, A., Davis, K.F., Ravi, S. and Runyan, C.W. 2013. Global desertification: Drivers and feedbacks. *Advances in Water Resources* 51: 326-344.
- D'Odorico, P., Okin, G.S. and Bestelmeyer, B.T. 2012. A synthetic review of feedbacks and drivers of shrub encroachment in arid grasslands. *Ecohydrology* 5(5): 520-530.
- Doran, J.W. and Zeiss, M.R. 2000. Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology* 15(1): 3-11.
- Duniway, M.C., Geiger, E.L., Minnick, T.J., Hoover, D.L. and Belnap, J. 2019. High vulnerability of restored biological soil crusts to extreme events. *Global Change Biology* 25(8): 2685-2697.
- Ehrenfeld, J.G. 2010. Ecosystem consequences of biological invasions. *Annual Review of Ecology, Evolution, and Systematics* 41: 59-80.
- Eldridge, D.J. and Greene, R.S.B. 1994. Microbiotic soil crusts: A review of their roles in soil and ecological processes in the rangelands of Australia. *Australian Journal of Soil Research* 32(3): 389-415.
doi:10.1071/SR9940389
- El-Sheikh, M.A., Thomas, J., Arif, I.A. and El-Sheikh, H.M. 2021. Ecology of inland sand dunes "nafuds" as a hyper-arid habitat, Saudi Arabia: Floristic and plant associations diversity. *Saudi Journal of Biological Sciences* 28(3): 1503-1513.
doi:10.1016/j.sjbs.2020.12.002
- Ezzat, S., Gaiballa, A., Majrashi, M.A., Alasmary, Z., Ibrahim, H.M., Harbi, M.A., Abldubise, A., Alqahtani, M.A. and Alghamdi, A.G. 2025. Comparative impacts of organic and inorganic fertilizers on the restoration of rangeland in the semi-arid regions of Saudi Arabia. *Sustainability* 17(20): 9253.
doi:10.3390/su17209253
- Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D. and Knapp, A. 2003. The importance of land-use legacies to ecology and conservation. *BioScience* 53(1): 77-88.
- Friedel, M.H. 1991. Range condition assessment and the concept of thresholds: A viewpoint. *Journal of Range Management* 44(5): 422-426.
- Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y. and Wu, B. 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity* 8(4): 284-293.
doi:10.1016/j.ecocom.2011.07.003

- Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decler, K. and Dixon, K.W. 2019. International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology* 27(S1): S1-S46.
doi:10.1111/rec.13035
- García, C., Hernández, T. and Roldán, A. 1997. Changes in microbial activity after abandonment of cultivation in a semiarid Mediterranean environment. *Journal of Environmental Quality* 26(1): 285-291.
- Gomaa, N.H., Hegazy, A.K. and Alhaithloul, H.A.S. 2023. Facilitation by *Haloxylon persicum* shrubs enhances density and richness of soil seed bank of annual plants in a hyper-arid ecosystem. *Plants* 12(6): 1276.
doi:10.3390/plants12061276
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. and Moore, R. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* 202: 18-27.
- Groffman, P.M., Baron, J.S., Blett, T., Gold, A.J., Goodman, I., Gunderson, L.H., Levinson, B.M., Palmer, M.A., Paerl, H.W., Peterson, G.D., Poff, N.L., Rejeski, D.W., Reynolds, J.F., Turner, M.G., Weathers, K.C. and Wiens, J. 2006. Ecological thresholds: The key to successful environmental management or an important concept with no practical application? *Ecosystems* 9(1): 1-13.
- Hamza, M.A. and Anderson, W.K. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82(2): 121-145.
- Hannula, S.E., Heinen, R., Huberty, M., Steinauer, K., De Long, J.R., Jongen, R. and Bezemer, T.M. 2021. Persistence of plant-mediated microbial soil legacy effects in soil and inside roots. *Nature Communications* 12: 5686.
doi:10.1038/s41467-021-25971-z
- Harris, J. 2009. Soil microbial communities and restoration ecology: Facilitators or followers? *Science* 325(5940): 573-574.
- Harris, J.A., Hobbs, R.J., Higgs, E. and Aronson, J. 2006. Ecological restoration and global climate change. *Restoration Ecology* 14(2): 170-176.
- Hillel, D. 1998. *Environmental Soil Physics*. Academic Press.
- Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4: 1-23.
- Hopmans, J.W., Qureshi, A.S., Kisekka, I., Munns, R., Grattan, S.R., Rengasamy, P., Ben-Gal, A., Assouline, S., Javaux, M., Minhas, P.S., Raats, P.A.C., Skaggs, T.H., Wang, G., De Jong van Lier, Q., Jiao, H., Lavado, R.S., Lazarovitch, N., Li, B. and Taleisnik, E. 2021. Critical knowledge gaps and research priorities in global soil salinity. *Advances in Agronomy* 169: 1-191.
- Huxman, T.E., Snyder, K.A., Tissue, D., Leffler, A.J., Ogle, K., Pockman, W.T., Sandquist, D.R., Potts, D.L. and Schwinning, S. 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia* 141(2): 254-268.
- IPBES 2018. The IPBES Assessment Report on Land Degradation and Restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
- Janzen, H.H. 2016. The soil remembers. *Soil Science Society of America Journal* 80: 1429-1432.
doi:10.2136/sssaj2016.05.0143
- Jech, S.D., Dohrenwend, K., Day, N., Barger, N.N., Antoninka, A., Bowker, M.A., Reed, S.C. and Tucker, C.L. 2025. Developing biocrust field cultivation techniques for soil restoration: An assessment of bacterial communities. *Applied Soil Ecology* 206: 105861.
doi:10.1016/j.apsoil.2024.105861
- Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E., Mack, M.C., Meentemeyer, R.K., Metz, M.R., Perry, G.L.W., Schoennagel, T. and Turner, M.G. 2016. Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment* 14(7): 369-378.
- Karlen, D.L., Ditzler, C.A. and Andrews, S.S. 2003. Soil quality: Why and how? *Geoderma* 114(3-4): 145-156.
- Kéfi, S., Rietkerk, M., Alados, C.L., Pueyo, Y., Papanastasis, V.P., ElAich, A. and de Ruiter, P.C. 2007. Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature* 449(7159): 213-217.
- Kemp, P.R. 1989. Seed banks and vegetation processes in deserts. In: *Ecology of Soil Seed Banks* (Eds. M.A. Leck, V.T. Parker and R.L. Simpson), pp. 257-281. Academic Press.
- Kennedy, R.E., Yang, Z., Gorelick, N., Braaten, J., Cavalcante, L., Cohen, W.B. and Healey, S. 2018. Implementation of the LandTrendr algorithm on Google Earth Engine. *Remote Sensing* 10(5): 691.
- Kinloch, J.E. and Friedel, M.H. 2005. Soil seed reserves in arid grazing lands of central Australia. Part 1: Seed bank and vegetation dynamics. *Journal of Arid Environments* 60(1): 133-161.
- Kulmatiski, A., Beard, K.H., Stevens, J.R. and Cobbold, S.M. 2008. Plant-soil feedbacks: A meta-analytical review. *Ecology Letters* 11(9): 980-992.
- Kushbokov, A., Deák, B. and Valkó, O. 2025. Characteristics of soil seed bank in global

- drylands: A review. *Arid Land Research and Management* 39(3): 289-310.
doi:10.1080/15324982.2025.2467728
- Lajtha, K. and Schlesinger, W.H. 1988. The biogeochemistry of phosphorus cycling and phosphorus availability along a desert soil chronosequence. *Ecology* 69(1): 24-39.
- Lal, R. 2001. Soil degradation by erosion. *Land Degradation & Development* 12(6): 519-539.
- Lal, R. 2004. Carbon sequestration in dryland ecosystems. *Environmental Management* 33(4): 528-544.
- Lapsansky, E.R., Milroy, A.M., Andales, M.J. and Vivanco, J.M. 2016. Soil memory as a potential mechanism for encouraging sustainable plant health and productivity. *Current Opinion in Biotechnology* 38: 137-142.
doi:10.1016/j.copbio.2016.01.014
- Laycock, W.A. 1991. Stable states and thresholds of range condition on North American rangelands: A viewpoint. *Journal of Range Management* 44(5): 427-433.
- Li, Y., Ma, X., Yan, K., Cao, C., Zhu, X. and Liu, K. 2025. Satellite-observed greening of human-dominated ecosystems in global dryland. *Journal of Remote Sensing* 5: 0941.
doi:10.34133/remotesensing.0941
- Ludwig, J.A., Wilcox, B.P., Breshears, D.D., Tongway, D.J. and Imeson, A.C. 2005. Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86(2): 288-297.
- Macheroum, A., Sayada, N. and Chenchouni, H. 2025. Restoration of soil quality and improvement of physicochemical properties through grazing exclusion in arid and semi-arid rangelands. *Catena* 249: 108646.
doi:10.1016/j.catena.2024.108646
- Maestre, F.T., Benito, B.M., Berdugo, M., Concostrina-Zubiri, L., Delgado-Baquerizo, M., Eldridge, D.J., Guirado, E., Gross, N., Kéfi, S., Le Bagousse-Pinguet, Y., Ochoa-Hueso, R. and Soliveres, S. 2021. Biogeography of global drylands. *New Phytologist* 231(2): 540-558.
doi:10.1111/nph.17395
- Maestre, F.T., Bowker, M.A., Cantón, Y., Castillo-Monroy, A.P., Cortina, J., Escolar, C., Escudero, A., Lázaro, R. and Martínez, I. 2011. Ecology and functional roles of biological soil crusts in semi-arid ecosystems of Spain. *Journal of Arid Environments* 75(12): 1282-1291.
- Mayor, A.G., Kéfi, S., Bautista, S., Rodríguez, F., Cartení, F. and Rietkerk, M. 2013. Feedbacks between vegetation pattern and resource loss dramatically decrease ecosystem resilience and restoration potential in a simple dryland model. *Landscape Ecology* 28(5): 931-942.
doi:10.1007/s10980-013-9870-4
- MEA 2005. Ecosystems and Human Well-Being: Desertification Synthesis. World Resources Institute.
- Metternicht, G. and Zinck, J.A. 2003. Remote sensing of soil salinity: Potentials and constraints. *Remote Sensing of Environment* 85(1): 1-20.
- Monger, H.C., Sala, O.E., Duniway, M.C., Goldfus, H., Meir, I.A., Poch, R.M., Throop, H.L. and Vivoni, E.R. 2015. Legacy effects in linked ecological-soil-geomorphic systems of drylands. *Frontiers in Ecology and the Environment* 13(1): 13-19.
doi:10.1890/140269
- Moreno-de las Heras, M., Nicolau, J.M., Merino-Martín, L. and Wilcox, B.P. 2010. Plot-scale effects on runoff and erosion along a slope degradation gradient. *Water Resources Research* 46(4): W04503.
doi:10.1029/2009WR007875
- Nawaz, M.F., Bourrié, G. and Trolard, F. 2013. Soil compaction impact and modelling: A review. *Agronomy for Sustainable Development* 33(2): 291-309.
- Nieland, M.A. and Keiser, A.D. 2025. Using ecological restoration to disentangle the mechanisms and longevity of soil functional legacies. *Functional Ecology* 39(9): 2193-2204.
doi:10.1111/1365-2435.70123
- Noy-Meir, I. 1973. Desert ecosystems: Environment and producers. *Annual Review of Ecology and Systematics* 4: 25-51.
- Ogle, D. and St. John, L. 2009. Plants for Saline to Sodic Soil Conditions. Technical Note Plant Materials No. 9A, Revision. USDA Natural Resources Conservation Service, Boise, Idaho and Salt Lake City, Utah, USA.
- Okin, G.S., Gillette, D.A. and Herrick, J.E. 2006. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. *Journal of Arid Environments* 65(2): 253-275.
- Okin, G.S., Murray, B. and Schlesinger, W.H. 2001. Degradation of sandy arid shrubland environments: Observations, process modelling, and management implications. *Journal of Arid Environments* 47(2): 123-144.
- Padisák, J. 1992. Seasonal succession of phytoplankton in a large shallow lake (Balaton, Hungary): A dynamic approach to ecological memory, its possible role and mechanisms. *Journal of Ecology* 80(2): 217-230.
doi:10.2307/2261008
- Peddle, S.D., Hodgson, R.J., Borrett, R.J., Brachmann, S., Davies, T.C., Erickson, T.E., Liddicoat, C., Muñoz-Rojas, M., Robinson, J.M., Watson, C.D., Krauss, S.L. and Breed, M.F. 2025. Practical

- applications of soil microbiota to improve ecosystem restoration: Current knowledge and future directions. *Biological Reviews* 100(1): 1-18. doi:10.1111/brv.13124
- Perkins, L.B. and Nowak, R.S. 2013. Native and non-native grasses generate common types of plant-soil feedbacks by altering soil nutrients and microbial communities. *Oikos* 122(2): 199-208.
- Pierson, F.B., Williams, C.J. and Robichaud, P.R. 2015. Assessing impacts of fire and post-fire mitigation on runoff and erosion from rangelands. Great Basin Fact Sheet Series No. 11. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA, pp. 1-6.
- Pointing, S.B. and Belnap, J. 2012. Microbial colonization and controls in dryland systems. *Nature Reviews Microbiology* 10(8): 551-562.
- Právělie, R. 2016. Drylands extent and environmental issues: A global approach. *Earth-Science Reviews* 161: 259-278.
- Qadir, M., Oster, J.D., Schubert, S., Noble, A.D. and Sahrawat, K.L. 2007. Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy* 96: 197-247.
- Rabot, E., Wiesmeier, M., Schlüter, S. and Vogel, H.J. 2018. Soil structure as an indicator of soil functions: A review. *Geoderma* 314: 122-137.
- Rahmati, M., Or, D., Amelung, W., Bauke, S.L., Bol, R., Hendricks Franssen, H.-J., Montzka, C., Vanderborght, J. and Vereecken, H. 2023. Soil is a living archive of the Earth system. *Nature Reviews Earth & Environment* 4: 421-423. doi:10.1038/s43017-023-00454-5
- Ravi, S., Breshears, D.D., Huxman, T.E. and D'Odorico, P. 2010. Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology* 116(3-4): 236-245.
- Reij, C., Tappan, G. and Smale, M. 2009. Agroenvironmental Transformation in the Sahel: Another Kind of Green Revolution. IFPRI Discussion Paper 00914. International Food Policy Research Institute.
- Rengasamy, P. 2006. World salinization with emphasis on Australia. *Journal of Experimental Botany* 57(5): 1017-1023.
- Requena, N., Perez-Solis, E., Azcón-Aguilar, C., Jeffries, P. and Barea, J.M. 2001. Management of indigenous plant-microbe symbioses aids restoration of desertified ecosystems. *Applied and Environmental Microbiology* 67(2): 495-498.
- Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernández, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M. and Walker, B. 2007. Global desertification: Building a science for dryland development. *Science* 316(5826): 847-851.
- Rietkerk, M., Dekker, S.C., de Ruiter, P.C. and van de Koppel, J. 2004. Self-organized patchiness and catastrophic shifts in ecosystems. *Science* 305(5692): 1926-1929.
- Schaefer, V. 2009. Alien invasions, ecological restoration in cities and the loss of ecological memory. *Restoration Ecology* 17(2): 171-176. doi:10.1111/j.1526-100X.2008.00513.x
- Scheffer, M. 2009. *Critical Transitions in Nature and Society*. Princeton University Press.
- Schimel, J.P. 2018. Life in dry soils: Effects of drought on soil microbial communities and processes. *Annual Review of Ecology, Evolution, and Systematics* 49: 409-432.
- Schlesinger, W.H. and Pilmanis, A.M. 1998. Plant-soil interactions in deserts. *Biogeochemistry* 42(1-2): 169-187.
- Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science* 247(4946): 1043-1048.
- Setia, R., Gottschalk, P., Smith, P., Marschner, P., Baldock, J., Setia, D. and Smith, J. 2013. Soil salinity decreases global soil organic carbon stocks. *Science of the Total Environment* 465: 267-272.
- Seymour, C.L., Milton, S.J., Joseph, G.S., Dean, W.R.J., Dithlobolo, T. and Cumming, G.S. 2010. Twenty years of rest returns grazing potential, but not palatable plant diversity, to Karoo rangeland, South Africa. *Journal of Applied Ecology* 47(4): 859-867.
- Shackelford, N., Paterno, G.B., Winkler, D.E., Erickson, T.E., Leger, E.A., Svejcar, L.N., Breed, M.F., Faist, A.M., Harrison, P.A., Curran, M.F., Guo, Q., Kirmer, A., Law, D.J., Mganga, K.Z., Munson, S.M., Porensky, L.M., Quiroga, R.E., Török, P. et al. 2021. Drivers of seedling establishment success in dryland restoration efforts. *Nature Ecology & Evolution* 5(9): 1283-1290. doi:10.1038/s41559-021-01510-3
- Sowards, T.G., Hamilton, B.T., Aanderud, Z.T., Petersen, S.L., St. Clair, S.B. and Madsen, M.D. 2025. Improving seedling recruitment and dryland restoration using a targeted fungicide seed coating. *Restoration Ecology* 33(2): e14312. doi:10.1111/rec.14312
- Suding, K.N. and Hobbs, R.J. 2009. Threshold models in restoration and conservation: A developing framework. *Trends in Ecology & Evolution* 24(5): 271-279.
- Suding, K.N., Gross, K.L. and Houseman, G.R. 2004. Alternative states and positive feedbacks in

- restoration ecology. *Trends in Ecology & Evolution* 19(1): 46-53.
- Sumner, M.E. 1993. Sodic soils: New perspectives. *Australian Journal of Soil Research* 31(6): 683-750.
- Targulian, V.O. and Bronnikova, M.A. 2019. Soil memory: Theoretical basics of the concept, its current state, and prospects for development. *Eurasian Soil Science* 52(3): 229-243. doi:10.1134/S1064229319030116
- Targulian, V.O. and Goryachkin, S.V. 2004. Soil memory: Types of record, carriers, hierarchy and diversity. *Revista Mexicana de Ciencias Geológicas* 21(1): 1-8.
- Thurrow, T.L. 1991. Hydrology and erosion. In: *Grazing Management: An Ecological Perspective* (Eds. R.K. Heitschmidt and J.W. Stuth), pp. 141-159. Timber Press.
- Tlili, A., Neffati, M., Dadi, K. and Ouled Belgacem, A. 2026. Contrasting soil seed bank and vegetation dynamics between protected and disturbed arid rangelands in Southern Tunisia. *Frontiers in Plant Science* 17: 1743624. doi:10.3389/fpls.2026.1743624
- Tongway, D.J. and Ludwig, J.A. 1996. Rehabilitation of semiarid landscapes in Australia. I. Restoring productive soil patches. *Restoration Ecology* 4(4): 388-397.
- Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8(2): 127-150.
- Turnbull, L., Wainwright, J. and Brazier, R.E. 2008. A conceptual framework for understanding semi-arid land degradation: Ecohydrological interactions across multiple space and time scales. *Ecohydrology* 1(1): 23-34.
- UNCCD. 2017. *The Global Land Outlook*, First Edition. United Nations Convention to Combat Desertification, Bonn, Germany.
- UNCCD. 2022. *Global Land Outlook*, Second Edition: Land Restoration for Recovery and Resilience. United Nations Convention to Combat Desertification.
- Valentin, C. and Bresson, L.M. 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. *Geoderma* 55(3-4): 225-245.
- van de Koppel, J., Rietkerk, M. and Weissing, F.J. 1997. Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems. *Trends in Ecology & Evolution* 12(9): 352-356.
- Verbesselt, J., Hyndman, R., Newnham, G. and Culvenor, D. 2010. Detecting trend and seasonal changes in satellite image time series. *Remote Sensing of Environment* 114(1): 106-115.
- Wang, L., D'Odorico, P., Evans, J.P., Eldridge, D.J., McCabe, M.F., Caylor, K.K. and King, E.G. 2012. Dryland ecohydrology and climate change: Critical issues and technical advances. *Hydrology and Earth System Sciences* 16(8): 2585-2603.
- Washington-Allen, R.A., West, N.E., Ramsey, R.D. and Efroymson, R.A. 2006. A protocol for retrospective remote sensing-based ecological monitoring of rangelands. *Rangeland Ecology & Management* 59(1): 19-29.
- Webb, N.P., Herrick, J.E., Duniway, M.C. and Millan, M.J. 2014. Ecological site-based assessments of wind and water erosion: Informing accelerated soil erosion management in rangelands. *Ecological Applications* 24(6): 1405-1420.
- Whisenant, S.G. 1999. *Repairing Damaged Wildlands: A Process-Oriented, Landscape-Scale Approach*. Cambridge University Press.
- Whitford, W.G. 2002. *Ecology of Desert Systems*. Academic Press.
- Wilcox, B.P., Breshears, D.D. and Allen, C.D. 2003. Ecohydrology of a resource-conserving semiarid woodland: Effects of scale and disturbance. *Ecological Monographs* 73(2): 223-239.
- Wood, G.V., Liddicoat, C., Robinson, J.M. and Breed, M.F. 2026. Restoring soil and sediment microbiomes in the Anthropocene. *Nature Reviews Microbiology*. doi:10.1038/s41579-026-01307-w
- Zhang, B., He, C., Burnham, M. and Zhang, L. 2016. Evaluating the coupling effects of climate aridity and vegetation restoration on soil erosion over the Loess Plateau in China. *Science of the Total Environment* 539: 436-449.
- Zhu, Z. and Woodcock, C.E. 2014. Continuous change detection and classification of land cover using all available Landsat data. *Remote Sensing of Environment* 144: 152-171.

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