

Supplementary Material

Abbreviations used in this Supplementary Material

BSC, biological soil crust; EC, electrical conductivity; ECe, electrical conductivity of the saturation extract; ESP, exchangeable sodium percentage; EVI, enhanced vegetation index; GEE, Google Earth Engine; LST, land surface temperature; NDVI, normalized difference vegetation index; SAR, sodium adsorption ratio; SAVI, soil-adjusted vegetation index; SMRF, Soil Memory-Based Restoration Framework; SOC, soil organic carbon.

Table S1. Search architecture, eligibility criteria, and coding framework

Section	Component	Specification
Search strategy	Review approach	Critical integrative review based on purposive evidence identification and mechanism-based synthesis. The review was not designed as a systematic review or meta-analysis.
Search strategy	Evidence fields	Soil science, dryland ecology, restoration ecology, ecohydrology, rangeland management, salinity and sodicity, biological soil crusts, seed-bank dynamics, land degradation, and geospatial monitoring.
Search strategy	Literature sources	Web of Science, Scopus, ScienceDirect, SpringerLink, Wiley Online Library, and Taylor & Francis. Google Scholar was used as a supplementary discovery source.
Search strategy	Publication period	Searches covered literature available through August 2026, while earlier foundational studies were retained where directly relevant to the concepts and mechanisms examined.
Search strategy	Core search string 1	"soil memory" AND drylands
Search strategy	Core search string 2	"legacy effects" AND soil degradation
Search strategy	Core search string 3	"dryland restoration failure"
Search strategy	Core search string 4	"functional thresholds" AND restoration
Search strategy	Core search string 5	"soil resilience" AND arid ecosystems
Search strategy	Core search string 6	"salinity" AND "sodicity" AND dryland restoration
Search strategy	Core search string 7	"soil compaction" AND dryland restoration
Search strategy	Core search string 8	"biological soil crust" AND restoration
Search strategy	Core search string 9	"seed bank" AND degraded drylands
Search strategy	Core search string 10	"plant-soil feedback" AND restoration
Search strategy	Core search string 11	"hydrological restoration" AND drylands
Search strategy	Search-string use	The strings represent the core conceptual combinations documented during development of the review. Terminology was broadened where necessary to capture related literature across the different evidence fields. They are reported as the review search architecture rather than as database-specific reproducible syntax.
Eligibility criteria	Included evidence	Peer-reviewed empirical studies, theoretical papers, major review articles, foundational soil-science literature, restoration standards, relevant methodological studies, and authoritative international reports.
Eligibility criteria	Conceptual relevance	Sources were retained when they contributed evidence relevant to dryland degradation, persistent soil constraints, restoration or rehabilitation outcomes, threshold behavior, ecosystem recovery, soil-water-vegetation interactions, or diagnostic and monitoring approaches.
Eligibility criteria	Dryland relevance	Evidence was prioritized when it originated from arid, semi-arid, dry sub-humid, rangeland, desert, or other water-limited systems, or when the mechanism described had clear relevance to dryland restoration.
Eligibility criteria	Exclusion criterion 1	Studies focused on humid or tropical systems without a clear transferable relationship to dryland processes.
Eligibility criteria	Exclusion criterion 2	Purely agronomic yield trials that did not contribute to interpretation of degradation, restoration, rehabilitation, or recovery processes.
Eligibility criteria	Exclusion criterion 3	Sources that were inaccessible, unverifiable, or insufficiently documented to support the interpretation for which they were considered.

Table S1. *Cont..*

Section	Component	Specification
Eligibility criteria	Exclusion criterion 4	Publications lacking relevant soil, hydrological, vegetation, geospatial, biological, restoration, or management information.
Eligibility criteria	Selection logic	Source selection was purposive rather than exhaustive. Studies were retained for their ability to demonstrate, contrast, or connect mechanisms relevant to soil memory and restoration response rather than to estimate the frequency of those mechanisms in the published literature.
Coding framework	Conceptual foundation	Definition and boundaries of soil memory and its relationship to soil health, soil quality, legacy effects, ecological memory, hysteresis, and restoration potential.
Coding framework	Soil-memory domain	Chemical, physical, biological, hydrological, management-imprinted, or coupled memory.
Coding framework	Source/evidence field	Dryland ecology, restoration ecology, soil chemistry and physics, biological memory, ecohydrology, rangeland/management evidence, or geospatial monitoring.
Coding framework	Geographic context	Region or dryland system represented by the source where this information was relevant to interpretation.
Coding framework	Degradation legacy	Historical or persistent constraint described by the study, such as salinity, sodicity, compaction, crusting, erosion, seed-bank depletion, biological-soil-crust disturbance, altered hydrology, or interacting legacies.
Coding framework	Intervention type	Protection or enclosure, passive recovery, assisted natural regeneration, seeding or planting, soil amendment, hydrological treatment, biological intervention, structural stabilization, or combined treatment.
Coding framework	Threshold logic	Evidence indicating reversible, conditionally reversible, threshold-dependent, persistent, or potentially functionally irreversible behavior under the stated restoration objective.
Coding framework	Restoration outcome	Successful recovery, partial recovery, immediate establishment failure, delayed decline, apparent greening without functional recovery, structural failure, management-related failure, or other reported response.
Coding framework	Monitoring logic	Aboveground vegetation response, soil chemical properties, soil physical condition, infiltration or runoff response, soil-moisture persistence, biological indicators, geospatial trajectories, or combinations of these.
Coding framework	Use in synthesis	The coding categories were used to organize the narrative synthesis by mechanism and to examine how inherited constraints could be linked to restoration failure types, threshold behavior, intervention sequencing, and monitoring requirements within SMRF.

Table S2. *Evidence fields supporting the soil-memory framework*

Evidence field	Core focus	Contribution to this review	Main gap addressed by SMRF
Dryland ecology	Rainfall pulses, resource islands, patch dynamics, shrub feedbacks, and desertification.	Explains why dryland responses are episodic, spatially uneven, and nonlinear.	Weak translation into operational restoration decisions.
Restoration ecology	Failure, thresholds, resilience, alternative states, recovery trajectories, and standards.	Explains why interventions may succeed, stall, or shift toward unexpected outcomes.	Soil constraints are often under-specified before intervention.
Soil chemistry and physics	Salinity, sodicity, compaction, crusting, SOC loss, and root-zone constraints.	Explains how inherited soil conditions restrict establishment and recovery.	Constraints are often treated as static diagnosis rather than functional memory.
Biological memory	Seed banks, microbes, mycorrhizae, biological soil crusts, and invasion legacies.	Explains why protection alone may fail where biological recovery capacity has been lost.	Biological indicators are often separated from hydrology and soil-surface diagnosis.
Geospatial monitoring	GEE, NDVI/EVI, LandTrendr, time-series trajectories, and field validation.	Supports landscape-scale screening of degradation and recovery signals.	Remote greening is often reported before soil-function recovery is confirmed.

Table S3. Geospatial and diagnostic infrastructure for applying SMRF at landscape scale

Layer	Main tools or indicators	Main output	Value for soil-memory diagnosis	Risk if omitted
Remote sensing	Landsat, Sentinel-2, NDVI, EVI, SAVI, bare soil index, LST, albedo.	Spatial screening and time-series trajectories.	Identifies where vegetation, surface exposure, heat, and moisture-related change are occurring.	Greening may be mistaken for genuine recovery.
Cloud processing	Google Earth Engine.	Long-term image stacks and regional processing.	Makes SMRF scalable across large dryland landscapes.	Large areas remain visually assessed only.
Statistical computing	R, Python, trend tests, machine learning, breakpoint detection.	Screening maps and uncertainty surfaces.	Supports landscape stratification and identifies areas requiring field verification.	Spatial screening becomes difficult to reproduce or validate.
Field diagnosis	Crusting, infiltration, erosion, effective root depth, and surface stability.	Process confirmation.	Explains how the soil surface is functioning on the ground.	Remote signals remain ambiguous.
Laboratory diagnosis	ECe, or EC with the extraction method reported; SAR; ESP; SOC; texture; nutrients; and microbial indicators.	Subsurface and biological constraint confirmation.	Confirms soil conditions that cannot be assigned reliably from imagery alone.	Intervention choice remains poorly supported without ground confirmation.
Decision layer	SMRF class, threshold status, and pathway sequence.	Restoration prescription and monitoring plan.	Converts evidence into site-specific restoration action.	Data collection does not translate into improved outcomes.
Feasibility context	Current grazing, access, tenure, enforcement, and maintenance	Feasibility record	Separates current implementation constraints from persistent soil-memory domains	A technically suitable pathway may be selected where implementation conditions cannot sustain it

Table S4. Key research gaps for operationalizing soil memory in dryland restoration

Knowledge gap	Current limitation	Research priority	Expected contribution
Operational definition	Soil memory is used inconsistently across disciplines.	Establish measurable domain-based definitions.	Comparable diagnosis across studies and regions.
Threshold calibration	Local thresholds remain poorly known for many dryland soils.	Test indicators across textures, aridity gradients, and degradation histories.	Better rules for pathway selection and feasibility assessment.
Geospatial scaling	Remote sensing and field-based soil diagnosis are rarely integrated within the same restoration assessment.	Develop screening maps that prioritize field verification and are calibrated against ground measurements.	Clearer separation of remotely observed change from confirmed recovery of soil function.
Biological memory	Seed banks, BSC condition, and microbial and mycorrhizal functions remain undermeasured in many restoration studies.	Include constraint-specific biological measurements in restoration trials and monitoring.	Stronger basis for identifying the limiting biological process and selecting an appropriate treatment.
Time scale	Short monitoring windows dominate restoration evaluation.	Establish long-term dryland observatories.	Better detection of delayed failure and persistent recovery.
Management and implementation context	Current grazing pressure, access, tenure, enforcement, and maintenance are often reported separately from soil diagnosis.	Pair soil-memory measurements with explicit records of current disturbance and implementation conditions.	Clearer separation between persistent soil legacies and feasibility constraints.

Table S5. Expanded cross-regional evidence matrix linking soil memory to dryland restoration outcomes

Region / system	Study or evidence basis	Evidence reported by the cited source(s)	Soil-memory interpretation in this review	SMRF implication	Main limitation of inference	Reference(s)
Global dryland seeding projects	Multi-site global synthesis	Across 174 sites on six continents, 17% of projects had no establishment of any seeded species, and seeded-species occurrence declined as projects matured	Site conditions contribute to restoration response together with seed traits, seeding rate, aridity, and species identity	Diagnose site constraints before repeated seeding and monitor beyond initial establishment	The synthesis identifies predictors of recruitment but does not assign soil-memory classes	(Shackelford <i>et al.</i> , 2021)
US Southwest and Great Basin	Invasion and degradation studies	Annual-grass invasion altered soil biota; sandy shrubland degradation involved aeolian redistribution and loss of soil resources	Biological and physical legacies can interact with vegetation change	Assess soil biota, invasion history, surface stability, and erosion before selecting treatment	These studies are not direct tests of SMRF or a single restoration treatment	(Belnap and Phillips, 2001; Okin <i>et al.</i> , 2001)
Sahel agro-pastoral systems	Regional synthesis and remote-sensing evidence	Farmer-led soil and water conservation and natural regeneration rehabilitated degraded land; regional woody-cover patterns also reflected land management	Hydrological processes and current management can jointly influence recovery	Diagnose hydrological constraints and record management separately as feasibility	The sources do not directly measure soil memory as defined in this review	(Reij <i>et al.</i> , 2009; Brandt <i>et al.</i> , 2018)
Karoo rangelands, South Africa	Long-term exclosure study	Twenty years of rest restored grazing potential but not palatable plant diversity	Partial recovery may remain after pressure is removed	Assess recruitment, propagules, composition, and soil condition before assigning a biological pathway	The study does not establish seed-bank depletion or another specific biological mechanism	(Seymour <i>et al.</i> , 2010)
Saudi inland sand systems	Protected vegetation survey and seed-bank study	Protected nafud vegetation retained diverse plant associations; <i>Haloxyylon persicum</i> shrubs increased germinable seed-bank density and richness beneath canopies	Aeolian context and shrub microsites can influence propagule retention and recruitment	Assess sand stability, safe sites, propagule availability, and moisture before broad revegetation	Neither study tests a complete active restoration package	(El-Sheikh <i>et al.</i> , 2021; Gomaa <i>et al.</i> , 2023)
Southwestern Saudi restored sites	Restored-versus-comparison soil study	Restored and comparison areas differed in several soil physicochemical properties, with responses varying among sites	Chemical and physical soil condition may influence restoration response	Use baseline soil properties to stratify sites and interpret vegetation response	Restoration history and treatments differ among sites and SMRF was not tested	(Al-Ghamdi <i>et al.</i> , 2021)
Iberian semiarid hillslopes	Runoff-erosion field study and regional restoration review	Vegetation spatial pattern and surface condition were associated with runoff and sediment yield; restoration outcomes and constraints varied among settings	Physical and hydrological structure can influence recovery	Diagnose runoff connectivity, surface condition, and microsites before intervention	The sources do not test one standardized SMRF pathway	(Bautista <i>et al.</i> , 2007; Cortina <i>et al.</i> , 2011)

Table S5. Cont...

Region / system	Study or evidence basis	Evidence reported by the cited source(s)	Soil-memory interpretation in this review	SMRF implication	Main limitation of inference	Reference(s)
Loess Plateau, China	Landscape erosion-control and climate-restoration studies	Restoration and increasing vegetation cover were associated with reduced erosion and changes in runoff and sediment, alongside climate and engineering effects	Hydrological and physical processes interact with vegetation recovery	Interpret vegetation trajectories together with erosion, runoff, and climate	Attribution is multi-driver and cannot be assigned to vegetation restoration alone	(Fu <i>et al.</i> , 2011; Zhang <i>et al.</i> , 2016)
Australian semiarid landscapes	Rehabilitation and ecohydrological process studies	Productive soil patches and vegetation-runoff-erosion feedbacks regulate retention and redistribution of resources	Physical and hydrological patch structure can persist as a recovery constraint	Diagnose patch connectivity and resource redistribution before selecting treatment	These studies do not test the complete SMRF sequence	(Tongway and Ludwig, 1996; Ludwig <i>et al.</i> , 2005)
Biological soil-crust restoration studies	Review and restoration literature	BSC protection, cultivation, inoculation, and field transfer have been tested in different restoration settings, with variable field recovery.	Biological surface recovery may require direct intervention where natural recovery is slow	Measure BSC condition and recovery directly	Field performance remains strongly site-dependent	(Bowker, 2007; Antoninka <i>et al.</i> , 2020; Jech <i>et al.</i> , 2025)

Note: The matrix is a qualitative evidence-tracing tool, not a statistical database. The cited sources differ in study design, duration, measured variables, and objectives. Soil-memory classifications and SMRF implications are interpretations made in this review unless the cited source explicitly uses the same construct. Intervention labels are used only where the source directly reports the intervention.

Table S6. Evidence basis and calibration status of SMRF screening rules

SMRF rule	Decision indicator	Screening condition	Evidence basis	Status	Local calibration or decision requirement
R1. Chemical-first	ECe, ESP, SAR, drainage, and root-zone condition	A chemical constraint is evident relative to soil properties, species tolerance, and drainage	(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)	Locally interpreted screening rule	Texture, clay mineralogy, electrolyte concentration, drainage, and target-species tolerance
R2. Physical-first	Penetration resistance, crusting, effective rooting depth, and soil structure	A measured physical constraint limits rooting or emergence	(Hamza and Anderson, 2005; Batey, 2009; Nawaz <i>et al.</i> , 2013; Rabot <i>et al.</i> , 2018)	Local screening rule	Soil moisture at measurement, texture, rooting tolerance, crust continuity, and crust strength
R3. Hydrology-first	Infiltration, runoff, soil-moisture persistence, and flow connectivity	Rainfall is lost mainly as runoff or soil moisture does not persist long enough for establishment	(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)	Local screening rule	Rainfall regime, landform, surface condition, and target rooting depth

Table S6. Cont...

SMRF rule	Decision indicator	Screening condition	Evidence basis	Status	Local calibration or decision requirement
R4. Biological constraint-specific pathway	Native seed bank and recruitment, BSC condition, and direct microbial or mycorrhizal indicators where relevant	A specific biological limitation is supported relative to an appropriate local reference and satisfies the historical-link and persistence criteria defined in the conceptual foundation of the review	(Kemp, 1989; Eldridge and Greene, 1994; Belnap and Phillips, 2001; Requena <i>et al.</i> , 2001; Belnap and Eldridge, 2003; Kinloch and Friedel, 2005; Belnap, 2006; Harris <i>et al.</i> , 2006; Bowker, 2007; Chambers <i>et al.</i> , 2007; Kulmatiski <i>et al.</i> , 2008; Harris, 2009; Ehrenfeld, 2010; Maestre <i>et al.</i> , 2011; Pointing and Belnap, 2012; Perkins and Nowak, 2013; Delgado-Baquerizo <i>et al.</i> , 2016; Duniway <i>et al.</i> , 2019; Antoninka <i>et al.</i> , 2020; Hannula <i>et al.</i> , 2021; Peddle <i>et al.</i> , 2025)	Local-reference screening rule	Identify the biological bottleneck before treatment; calibration should reflect the ecological-site reference, propagule supply, BSC recovery context, and biological measurement method used
R5. Stabilize before planting	Bare ground, slope, runoff connectivity, and active erosion	Active erosion or runoff hazard is present. The 50–60% bare-ground and >15% slope combination is retained only as a published post-fire reference point	(Moreno-de las Heras <i>et al.</i> , 2010; Pierson <i>et al.</i> , 2015)	Published reference point, not a universal threshold	Local erosion susceptibility, disturbance history, soil, slope, and storm regime
R6. Sequenced package	Two or more interacting constraints	Multiple constraints interact or one constraint maintains another	Framework synthesis (Schlesinger <i>et al.</i> , 1990; Rietkerk <i>et al.</i> , 2004; Okin <i>et al.</i> , 2006; Ravi <i>et al.</i> , 2010; D’Odorico <i>et al.</i> , 2013; Bestelmeyer <i>et al.</i> , 2015; Monger <i>et al.</i> , 2015)	Framework decision rule	Sequence treatments according to causal dependency and the dominant bottleneck
R7. Land-use redesign	Management feasibility and endpoint feasibility under current and projected climate	Required management conditions cannot be maintained or the intended recovery state is not feasible	Framework synthesis and (Harris <i>et al.</i> , 2006; Wang <i>et al.</i> , 2012)	Context-dependent feasibility rule	Climate trajectory, land-use objective, access, tenure, enforcement, and maintenance