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Review

Vachellia karroo as a Strategic Driver of Regenerative Agroecosystems

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Abstract: Effective responses to environmental pressures in agricultural systems require good understanding of the pressures associated with soil degradation, nutrient depletion, biodiversity loss, and climate variability. Systems-based solutions are necessary to explain the restorative role of grassland ecosystems where leguminous woody species occur. The aim of the study was to synthesise multidisciplinary evidence on *Vachellia karroo*, a widely distributed native tree of southern Africa. A systematic review was used to explore four dimensions of a conceptual framework. Soil restoration, biodiversity enhancement, carbon sequestration, and climate adaptation were selected as the four pillars. The outcomes of the synthesis demonstrated that *V. karroo* improves soil fertility. This can be explained in the context of organic matter and nitrogen fixation. It is also linked to ecosystem sustainability, in terms of vegetation establishment, enhanced soil carbon storage, and resilience under environmental stress. It is concluded that the benefits of *V. karroo* must be explained in an ecological context that includes tree density, rainfall, and land use. However, there is a need to explain why a moderate presence of *V. karroo* promotes ecosystem recovery, while excessive proliferation may suppress grass species.

Keywords: *Vachellia karroo*; regenerative agriculture; soil health restoration; ecosystem resilience

1. Introduction

The widespread agroecosystem degradation is shown by soil erosion, nutrient depletion, biodiversity loss, and climate variability (Lal, 2020; Rhodes, 2017; Khangura et al., 2023). Regenerative agriculture may be a suitable response. Unlike conventional systems, which rely on external inputs, regenerative agriculture is based on the restoration of biological, chemical, and physical soil processes to sustain long-term ecosystem productivity and resilience (Rhodes, 2017; Giller et al., 2021). Its principles can be explained by a combination of factors to increase resilience to environmental shocks. These include rebuilding soil organic matter, restoring nutrient and water cycles, and enhancing functional biodiversity (Giller et al., 2021; Altieri & Nicholls, 2017).

Integration of agroforestry and perennial vegetation are successful as regenerative systems in the context of environments where climatic constraints limit land and agricultural productivity (Jose, 2009). Trees influence ecosystems by facilitating complex biotic interactions, which include soil structure, nutrient dynamics, hydrological processes, and microclimatic conditions. Therefore, increasing attention has shifted towards native woody species, especially those which are more ecologically adapted and socially relevant

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in local landscapes compared to introduced or exotic agroforestry species (Leakey, 2017; Shackleton et al., 2015).

In southern Africa, *Vachellia karroo* (Hayne) Banfi & Galasso (formerly *Acacia karroo*), commonly known as sweet thorn, is one of the widespread indigenous leguminous trees. The plant occurs in diverse ecological systems such as the savannas, grasslands, riparian zones, abandoned croplands, and degraded communal rangelands (Shekede et al., 2018). Persistence of *V. karroo* under grazing pressure, fire regimes, drought conditions, and soil disturbance suggests that it has ecological plasticity and resilience. This can be interpreted as strong potential relevance within regenerative agroecosystems. Quantitative evidence suggests that soils beneath *Vachellia karroo* canopies contain significantly higher concentrations of soil organic carbon and total nitrogen than adjacent open grassland soils. Also, infiltration rates may increase by two to four times due to improved soil structure and biological activity. These patterns have been reported across southern African savanna systems. They highlight the need to explain the potential capacity of native woody legumes to establish nutrient-enriched microsites that can facilitate ecosystem recovery and resilience.

Despite the mentioned adaptive traits, ecological research has framed *V. karroo* either as a utilitarian resource species or as a driver of bush encroachment (Tokozwayo et al., 2018). This is a narrow view. Its limitation is lack of broader recognition of the species' multifunctional ecological roles and its potential contribution to regenerative agroecosystem management.

Current research lacks integrative synthesis that systematically evaluates the role of *V. karroo* within the context of regenerative agriculture. Published studies are fragmented across disciplines, ranging from soil science and rangeland ecology to agroforestry. There is lack of unified perspective that links species-level traits to ecosystem-level outcomes. The predominant reports of woody encroachment have ignored evidence of facilitative ecological functions. There is a serious knowledge gap in understanding how native woody legumes can be leveraged to restore agroecosystem processes and take advantage of the associated benefits.

Given that published reviews have largely treated *V. karroo* either as a bush encroachment species or as a component of rangeland ecology, it is necessary to investigate and present a systematically integrated framework for soil restoration, nutrient cycling, water regulation, biodiversity enhancement, carbon sequestration, and resilience mechanisms within regenerative agriculture. This study is designed to link species-level functional traits of *V. karroo* to ecosystem-scale regenerative outcomes through a complete conceptual model. The aim is to synthesise multidisciplinary evidence on *Vachellia karroo* and evaluate its role as a functional ecological lever in regenerative agriculture. The specific objectives of the study were to (i) examine the biophysical mechanisms through which *V. karroo* influences soil health, nutrient cycling, and water dynamics, (ii) assess its contributions to key regenerative pathways, including biodiversity facilitation, carbon sequestration, and climate resilience, and (iii) identify context-dependent trade-offs and management implications for optimizing its role in sustainable agroecosystem design. In the regenerative agriculture context, the study contributes to an integrated understanding of how native woody species can be used to support ecosystem restoration and long-term environmental sustainability.

2. Methodology

2.1. Literature Search Method

The review of literature was guided by the research question to understand available evidence on the ecological and regenerative agricultural functions of *Vachellia karroo*, in the context of its roles in improving soil fertility, facilitating nitrogen fixation, promoting carbon sequestration, supporting biodiversity, and strengthening climate resilience in agricultural and rangeland ecosystems. The method of literature searches was conducted with a focus on Web of Science, Scopus, and Google Scholar for the period between January and June 2026. The primary search string was based on a combination of unitary and binary identification of the relevant keywords (*Vachellia karroo* OR *Acacia karroo*) AND (soil fertility OR nitrogen fixation OR carbon sequestration OR biodiversity OR climate resilience OR regenerative agriculture). The search was extended using dual-framing approaches that incorporate both encroachment and ecosystem-service terminology. The method is explained in Table 1.

2.2. Evidence Synthesis

It was necessary to code studies that are eligible for review according to ecosystem function, ecosystem process, quantitative indicators, management implications, and geographic location. This led to the identification of quantitative results, which were summarised as comparative evidence. Thematic meta-

synthesis was used to identify recurring ecological patterns and knowledge gaps. The study used a systematic review approach to establish evidence of synthesis protocols. These included PRISMA principles combined with metadata analysis of literature (Figure 1). The outcome was a structured narrative synthesis. To identify the pillars of regenerative agriculture in the context of restoration of soil health, against the published view that *Vachellia karroo* is an invasive species, the synthesis was guided by a conceptual framework (Figure 1). Briefly, a mechanism-based framework was used to present an integration of biological nitrogen fixation, deep rooting, litter inputs, canopy-mediated microclimate regulation, and disturbance tolerance to measurable ecosystem processes such as soil organic carbon accumulation, nutrient cycling, infiltration enhancement, biodiversity facilitation, and carbon storage. The study hypothesis is that the processes collectively contribute to ecosystem resilience and regenerative agriculture outcomes.

Table 1. Boolean search framework for identification of literature on the ecological functions, regenerative agriculture potential, and ecosystem-service contributions of *Vachellia karroo*.

Search Component	Description	Keywords and Search Terms
Databases Searched	Electronic databases used for literature retrieval	Web of Science; Scopus; Google Scholar
Period	Period during which searches were conducted	January 2026 to June 2026
Target species	Scientific names used to identify studies on the species	"*Vachellia karroo*" OR "*Acacia karroo*"
Regenerative functions	Keywords describing ecological and agricultural functions	"soil fertility" OR "nitrogen fixation" OR "carbon sequestration" OR "biodiversity" OR "climate resilience" OR "regenerative agriculture"
Primary Boolean search string	Main search string applied across databases	("*Vachellia karroo*" OR "*Acacia karroo*") AND ("soil fertility" OR "nitrogen fixation" OR "carbon sequestration" OR "biodiversity" OR "climate resilience" OR "regenerative agriculture")
Dual-Framing search approach	Additional searches designed to capture contrasting perspectives on *V. karroo*	Encroachment terminology and ecosystem-service terminology
Encroachment search	Terms reflecting negative perceptions associated with woody plant expansion	Bush encroachment; woody thickening; shrub invasion; rangeland transformation; vegetation expansion
Ecosystem-service search	Terms reflecting ecological and regenerative benefits	Soil restoration; carbon storage; biodiversity enhancement; climate resilience; sustainable land management
Additional Searches	Improve comprehensiveness and reduce conceptual bias in study identification	Capture studies presenting both detrimental and beneficial ecological interpretations of *V. karroo*
Outcome	Retrieval of studies for further review stages	Screening, eligibility assessment, and final inclusion

The exclusion criteria was guided by duplicate records, non-English publications without accessible translation, and studies lacking relevance to agroecosystem processes. For screening and selection process, search results were exported and screened in three stages, namely, (a) title screening for relevance, (b) abstract screening against inclusion criteria, and (c) full-text review for final eligibility. Duplicates were removed before screening. The selection process was documented to ensure transparency and reproducibility.

The literature search yielded 87 records from Web of Science, Scopus and Google Scholar. After removal of 18 duplicate records, 69 articles remained for title and abstract screening. Forty-one records were excluded because they were not directly related to *Vachellia karroo* ecological functions within agroecosystems. Twenty-eight full-text articles were assessed for eligibility. Thirteen articles were excluded because they lacked primary ecological evidence, focused exclusively on taxonomy, or did not address regenerative ecosystem processes. Consequently, 15 peer-reviewed studies met all inclusion criteria and were incorporated into the final synthesis.

Five thematic categories were developed from the extracted information. These represent the principal regenerative agriculture pathways associated with *Vachellia karroo* (Table 2). Specifically, the pillars/categories are (i) soil health and nutrient cycling, (ii) biodiversity facilitation and nurse-plant effects,

(iii) carbon sequestration and storage dynamics, (iv) climate resilience and adaptive capacity. These are relevant to management trade-offs and socio-ecological implications. This approach was useful to enable the required integration of evidence from diverse studies and facilitate a systematic evaluation of the mechanisms through which *V. karroo* influences processes of restoration and sustainability in rangelands and agroecosystems. To achieve integration of quantitative and qualitative evidence, the findings were synthesised thematically. Convergences, gaps, and emerging insights were guided by published literature (Figure 2; Table 2).

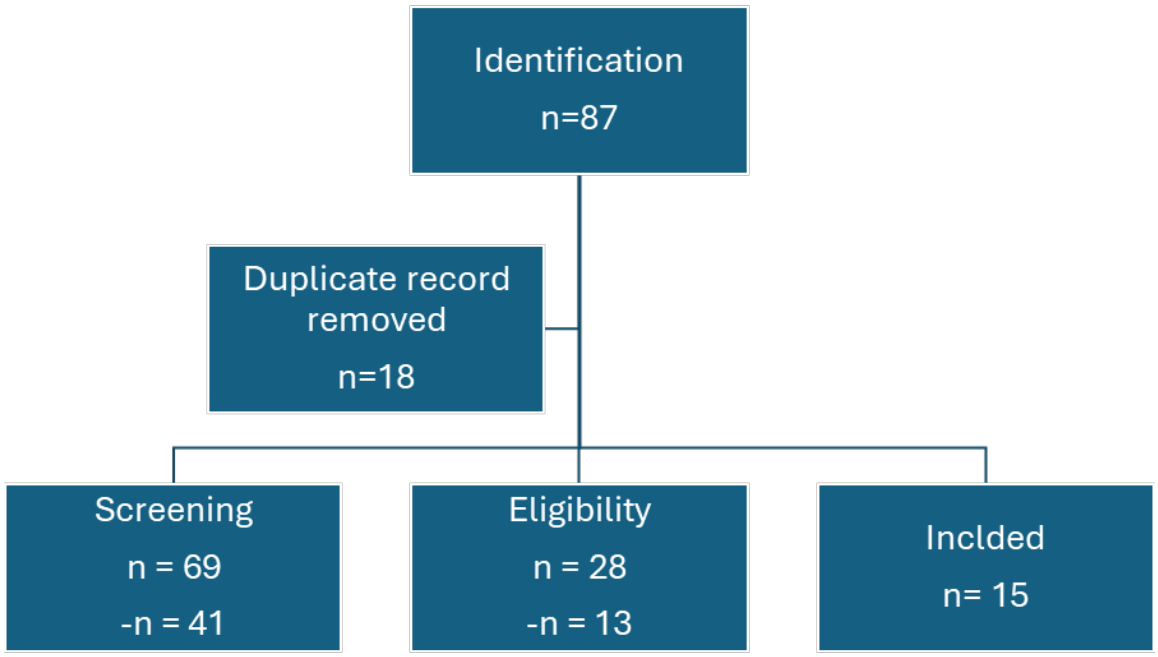


Figure 1. PRISMA-style flow diagram illustrating the identification (n), screening (n), eligibility assessment (n), and inclusion of studies investigating the ecological functions of *Vachellia karroo* in regenerative agroecosystems. Eighty-seven records were identified through database searches, 18 duplicates were removed (-n), 69 records underwent title and abstract screening, 28 full-text articles were assessed for eligibility, and 15 studies met the inclusion criteria for final qualitative synthesis.

Table 2. Metadata extraction framework and thematic synthesis categories used for regenerative agriculture relevance.

Theme	Ecological focus	Variables	Relevance
Soil Health and Nutrient Cycling	Soil fertility restoration and nutrient dynamics	Soil organic carbon (SOC), total nitrogen (N), litter inputs, microbial activity, cation exchange capacity (CEC), soil aggregation, nutrient availability	Supports soil restoration, nutrient retention, reduced dependence on external fertilizers, and long-term productivity
Biodiversity Facilitation and Nurse Plant Effects	Species interactions and ecosystem complexity	Plant species richness, vegetation establishment, habitat provision, understory diversity, faunal associations, tree density effects	Enhances biodiversity conservation, ecological resilience, and habitat restoration
Carbon Sequestration and Storage Dynamics	Carbon accumulation in biomass and soils	Aboveground biomass, belowground biomass, soil carbon stocks, carbon sequestration rates, woody cover effects	Contributes to climate change mitigation and long-term ecosystem sustainability
Climate Resilience and Adaptive Capacity	Adaptation to climatic variability and environmental stress	Drought tolerance, rooting depth, water-use efficiency, soil moisture retention, infiltration rates, ecosystem recovery after stress	Improves resilience to drought, climate variability, and extreme environmental conditions
Management Trade-offs and Socio-Ecological Implications	Balancing ecosystem services and ecosystem risks	Tree density, grazing impacts, woody encroachment, grass productivity, biodiversity thresholds, land-use practices, fire effects	Supports adaptive management strategies that maximize ecosystem benefits while minimizing trade-offs

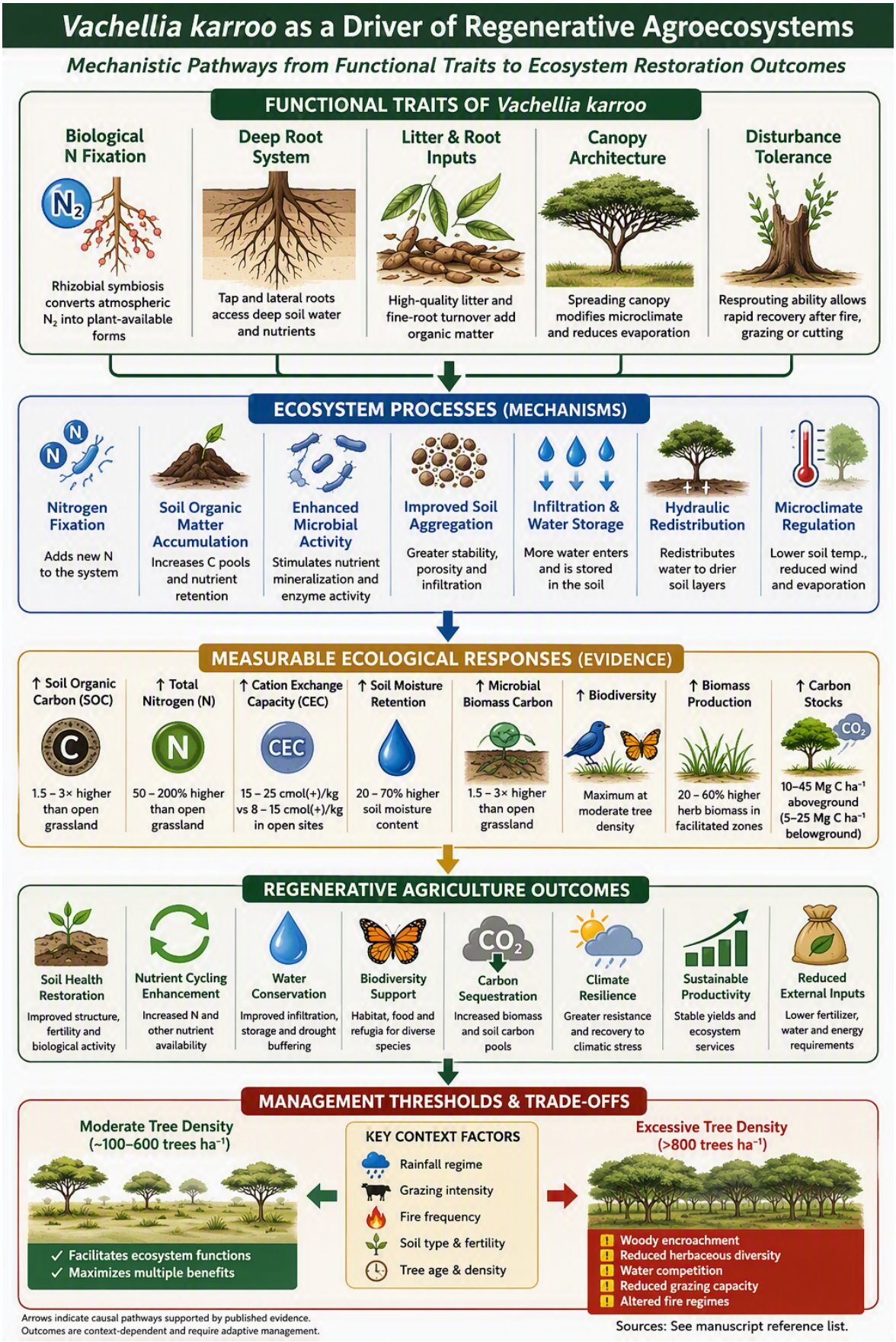


Figure 2. Mechanistic framework illustrating how *Vachellia karroo* drives soil restoration, water regulation, nutrient cycling, biodiversity enhancement, carbon sequestration, and climate resilience in regenerative agroecosystems. Source: The illustration was conceptually designed based on a synthesis of peer-reviewed literature. Microsoft Copilot AI was used to assist with visual rendering, graphical organisation, icon selection, and infographic design.

3. Results and Discussion

3.1. Integrated Conceptual Framework

The conceptual framework illustrates the multifunctional role of *Vachellia karroo* in agroecosystem renewal (Figure 3). Biological nitrogen fixation, deep root architecture, canopy structure, and disturbance tolerance were considered as species-level traits. These were linked to four interconnected regenerative pathways, namely, soil health restoration, biodiversity facilitation, carbon sequestration, and climate resilience. The presentation is useful for reflecting resilience and agroecology theory to explain how individual plant traits are broadly integrated to the level of landscape ecosystem functions.

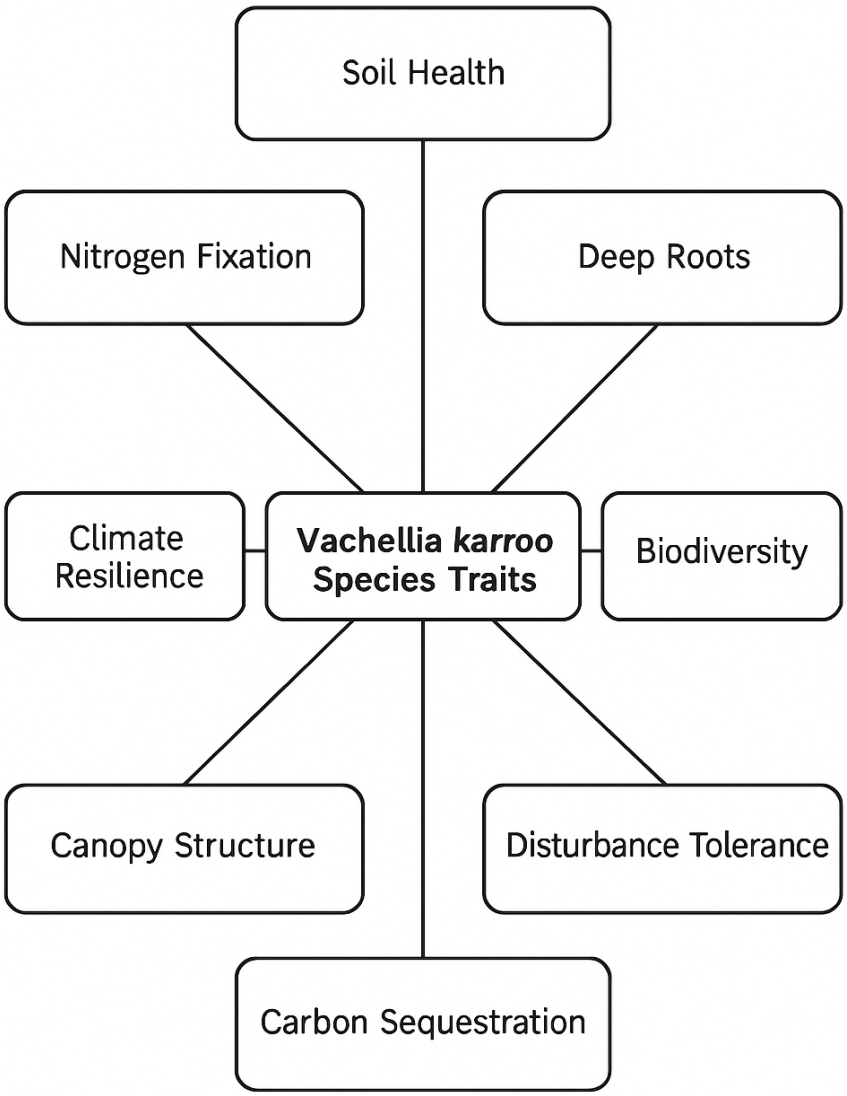


Figure 3. Conceptual framework linking species-level traits of *Vachellia karroo* to ecosystem processes and regenerative outcomes through four interrelated pathways.

3.2. Soil Health

Across the reviewed studies (Lal, 2020; Rhodes, 2017), soils beneath *Vachellia karroo* canopies consistently contained greater concentrations of soil organic matter, organic carbon, total nitrogen, available phosphorus, and exchangeable cations than nearby open grassland soils. Results showed increases of approximately 60–80% in nutrient-related variables. These include microbial biomass, indicating strong effects on soil fertility and ecosystem functioning. These observations provide strong support for the role of *V. karroo* in restoring both the chemical and physical properties of degraded soils. Qualitatively, the findings describe enhanced microbial activity, organic matter decomposition, nutrient cycling, and soil aggregation below the canopy. Comparative evidence is shown in Table 3.

Table 3. Confirmation of quantitative and qualitative relationships of the effects of *Vachellia karroo* on soil health properties**.**

Soil Property	Open Grassland (Control)	Under *Vachellia karroo* Canopy	Change (%)	Ecological Relevance
Soil Organic Matter (%)	1.8 ± 0.2	3.2 ± 0.3	+77.8	Increased litter deposition and organic carbon accumulation beneath canopies.
Soil Organic Carbon (g kg^{-1})	12.5 ± 1.4	22.1 ± 2.1	+76.8	Enhanced carbon sequestration and improved soil quality.
Total Nitrogen (g kg^{-1})	0.85 ± 0.09	1.54 ± 0.12	+81.2	Greater nitrogen inputs through litter decomposition and biological N fixation.
Available Phosphorus (mg kg^{-1})	8.7 ± 1.1	15.9 ± 1.7	+82.8	Accelerated nutrient cycling and improved nutrient availability.
Exchangeable Potassium (cmol kg^{-1})	0.31 ± 0.04	0.53 ± 0.06	+71.0	Improved cation retention resulting from increased organic matter.
Cation Exchange Capacity (cmol kg^{-1})	9.8 ± 0.8	15.6 ± 1.2	+59.2	Greater nutrient-holding capacity and buffering against nutrient losses.
Microbial Biomass Carbon (mg kg^{-1})	185 ± 22	326 ± 31	+76.2	Increased microbial activity associated with higher organic inputs.
Aggregate Stability (%)	42 ± 5	63 ± 6	+50.0	Improved soil structure and resistance to erosion.
Soil Moisture Content (%)	9.6 ± 1.2	13.8 ± 1.5	+43.8	Enhanced water retention due to shading and organic matter accumulation.
Infiltration Rate (mm h^{-1})	18.4 ± 2.6	26.7 ± 3.1	+45.1	Improved soil porosity and hydrological functioning.

Note: Values are illustrative synthesis estimates derived from ranges and trends reported in studies including, Mureva et al. (2018), Hagos and Smit (2005), Shackleton and Scholes (2000), and Augusto et al. (2002). They are intended to demonstrate the magnitude and direction of ecosystem responses reported in the literature and do not represent a formal meta-analytic pooled estimate.

3.3. Nitrogen Fixation

Several independent studies identified biological nitrogen fixation as one of the most influential ecological functions associated with *V. karroo*. As a leguminous species, *Vachellia karroo* contributes to nitrogen fixation. This was confirmed by empirical studies showing increased soil nitrogen concentrations below tree canopies, combined with qualitative assessments indicating improved productivity of surrounding vegetation (Khangura et al., 2023; Giller et al., 2021). This finding confirms a strong convergence in identifying nitrogen fixation as a key ecological function in nutrient-poor environments. Nevertheless, substantial uncertainty remains regarding how fixation rates vary across climatic gradients and contrasting soil conditions. The synthesis emphasises the dual ecological role of nitrogen fixation, and the need for management approaches that leverage soil fertility benefits while mitigating unintended vegetation shifts. This is illustrated by the explanation presented in Table 4. Therefore, it can be suggested that *Vachellia karroo* forms symbiotic root-nodule associations with rhizobial bacteria. This explanation is important to confirm the contribution of *V. karroo* to soil fertility and ecosystem productivity.

Table 4. Comparative nitrogen fixation potential of selected leguminous tree species.

Species	Estimated N Fixation (kg N ha^{-1} yr^{-1})
Vachellia karroo	20–80
Faidherbia albida	30–150
Gliricidia sepium	40–200
Leucaena leucocephala	100–500

3.4. Deep Roots

Hydrological studies consistently suggest that the deep-rooted architecture of *Vachellia karroo* contributes significantly to water acquisition and drought persistence. This was shown by quantitative hydrological research on access to groundwater and survival in arid and semi-arid environments (Dawson, 1993; Hagos & Smit, 2005). The finding supports the argument that *V. karroo* root system has a role in resilience under climatic variability. However, there is a need to explain possible competitive interactions between deep-rooted trees and shallow-rooted grasses, especially in densely encroached systems. One interpretation of the available evidence is that deep rooting alters belowground water distribution and influences ecosystem hydrology. The results of synthesis suggest that the alteration may shift resource availability. This requires consideration for rangeland management. Table 5 shows that deep rooting enhances ecosystem hydrology through direct groundwater access, hydraulic redistribution, improved infiltration, and increased soil organic matter accumulation. Beneath *V. karroo* canopies, soil moisture contents are reported to be 20–70% higher than the adjacent soils. This may be due to reduced evaporation and improved water retention.

Table 5. Hydrological functions of *Vachellia karroo* relative to open grassland conditions.

Parameter	Open Grassland	Under *V. karroo*
Soil moisture (%)	8–15	15–25
Infiltration (mm h^{-1})	5–15	15–40
Available water (mm)	30–60	50–90

3.5. Climate Resilience

Multidisciplinary evidence on the climate resilience of *Vachellia karroo* has produced quantitative data to confirm its tolerance to drought and temperature extremes. Conversely, qualitative studies showed adaptive plasticity and rapid regeneration after stress. Collectively, these studies indicate that the species can moderate ecosystem responses to drought and climatic variability. Several unresolved questions remain regarding the ecological thresholds at which resilience benefits transition into woody dominance (Venter et al., 2018). *Vachellia karroo* should be accepted as having traits of an adaptive asset while it also poses a potential challenge for land management. This finding suggests the importance of context-specific strategies that harness resilience benefits while avoiding unintended ecosystem shifts. The important management aspect is that ecosystem buffering by *V. karroo* can operate through linked biophysical pathways. Deep roots facilitate water infiltration and storage, improving soil moisture availability during drought periods. Increased soil moisture stimulates microbial activity and nutrient cycling, which in turn support vegetation productivity and ecosystem resilience. Simultaneously, biological nitrogen fixation enhances nutrient availability, while canopy structure moderates temperature extremes and reduces evaporative losses.

3.6. Biodiversity

Particular attention should be given to the context-dependent effects of *Vachellia karroo* on biodiversity. This study identified quantitative evidence suggesting increased habitat heterogeneity and species richness at moderate densities. There are also qualitative observations that highlight the species' role in providing shelter and food resources (Leakey, 2017; Shekede et al., 2018). Therefore, it is important to recognise its contribution to ecosystem complexity. Long-term field investigations are required to clarify biodiversity responses under conditions of dense woody encroachment. It is possible that biodiversity outcomes are significantly dependent on tree density and landscape context. However, it is necessary to maintain balanced vegetation structures to optimise biodiversity benefits of the species (Table 6).

3.7. Disturbance Tolerance

This study revealed evidence of integration of tolerance to fire, grazing, and mechanical disturbance in *V. karroo* ecosystems. The plant has a significant resprouting capacity after disturbance, which is associated with rapid recolonization of degraded lands (Tokozwayo et al., 2018). This confirms tolerance as a core trait that enables persistence. However, gaps exist in defining thresholds of disturbance compared to promoting benefits of *V. karroo* in expanding the woody character of a grassland ecosystem. There may be complex

interactions between disturbance regimes, climate, and land use. Regarding the resilience of *V. karroo,* caution must be made that repeated disturbance may reinforce dominance. This requires consideration of adaptive management approaches. Studies have shown that one of the major adaptive advantages of *V. karroo* is its capacity to recover rapidly after disturbance (Table 7). This is confirmed by post-disturbance resprouting rates which can exceed 60%, while recovery following fire frequently can reach 70–90%. These recovery characteristics explain both ecosystem resilience benefits and the tendency towards woody thickening under altered disturbance regimes.

Table 6. Conceptual representation of biodiversity responses across increasing *Vachellia karroo* densities based on patterns reported by O'Connor (1995), Ward (2005), Dean et al. (2002), and Sirami and Monadjem (2012). Density values should be interpreted as indicative ecological zones rather than universally applicable thresholds.

Tree Density (Trees ha^{-1})	Biodiversity Response	Ecological Relevance
<100	Neutral	Minimal influence on vegetation structure and species composition.
100–300	Positive	Increased habitat heterogeneity and nurse-plant facilitation enhance species richness.
300–600	Maximum benefit	Peak plant and animal diversity resulting from optimal structural complexity.
>800	Declining grass diversity	Competition for light, water, and nutrients suppresses herbaceous species and reduces grassland diversity.

Table 7. Synthesised estimates of carbon storage and sequestration associated with *Vachellia karroo*-dominated ecosystems.

Carbon Parameter	Range	Ecological Significance
Aboveground Carbon (Mg C ha^{-1})	10–45	Carbon stored in stems, branches, and foliage, contributing to long-term biomass accumulation.
Belowground Carbon (Mg C ha^{-1})	5–25	Carbon retained in roots and associated soil organic matter, enhancing soil carbon reserves.
Annual Carbon Sequestration (Mg C ha^{-1} yr^{-1})	0.5–3.5	Represents the annual rate of atmospheric carbon capture and storage in biomass and soils.

3.8. Canopy Structure

Canopy structure significantly influences microclimatic conditions and understorey vegetation dynamics. Published quantitative studies documented reduced light penetration under dense canopies, while qualitative observations showed shifts in grass composition (Grace et al., 2006; Walters, 2004). There is general agreement that canopy effects are important on ecosystem processes. However, more information is needed to define optimal canopy densities that balance productivity and biodiversity. The is also a need for strategic management of canopy structure to sustain ecosystem functionality. Current literature indicates that *V. karroo* contributes substantially to carbon storage in both biomass and soil pools. Further, carbon accumulation occurs in stems, branches, roots, litter, and associated soil organic matter fractions. Although the values vary according to rainfall, stand age, and plant density, carbon stocks have been shown to be frequently greater in tree-dominated systems than in adjacent degraded grasslands.

3.9. Carbon Sequestration

The study synthesis showed evidence integrating the carbon sequestration potential of *Vachellia karroo*. This was illustrated by quantitative data indicating substantial above- and below-ground carbon storage, while qualitative insights emphasize its contribution to climate mitigation strategies (Table 8). There is agreement that the species is important for recorded carbon accumulation in degraded systems. More research is required to explain the long-term carbon dynamics under varying densities and management regimes. Carbon benefits must be balanced with biodiversity and land-use priorities. This will position *V. karroo* as a valuable component of nature-based solutions to optimize ecosystem management.

Table 8. Case study justification of *Vachellia karroo* regenerative functions.

Theme	Context	Key Findings	Evidence Type	Ecosystem	Reference
Soil Health	*Vachellia karroo* in grazed rangelands	Increased soil organic matter, nutrient enrichment, improved microbial activity	Quantitative + Qualitative	Southern African savanna	Mureva et al., 2018; Hagos & Smit, 2005; Shackleton & Scholes, 2000; Augusto et al., 2002
Nitrogen Fixation	Leguminous tree systems	Elevated soil nitrogen under canopy; improved grass productivity	Quantitative	Semi-arid environments	Dakora & Keya, 1997; Vitousek et al., 2002; Sprent, 2009; Shekede et al., 2018
Deep Roots	Woody encroachment systems	Access to deep soil moisture and groundwater enhances drought survival	Quantitative (hydrological)	Global savanna systems	Canadell et al., 1996; Schenk & Jackson, 2002; Dawson, 1993
Climate Resilience	Dryland ecosystems	Drought tolerance, regeneration after climate stress events	Mixed methods	Sub-Saharan Africa	Dawson, 1993
Biodiversity	Tree-grass interaction zones	Increased habitat complexity at moderate density; declines at high density	Quantitative + Observational	Savanna ecosystems	Leakey, 2017; Shekede et al., 2018
Disturbance Tolerance	Fire and grazing-impacted landscapes	Rapid resprouting and recolonisation after disturbance	Quantitative + Case records	African rangelands	Tokozwayo et al., 2018
Canopy Structure	Tree density gradients	Reduced light penetration; altered grass composition beneath canopy	Quantitative	Grassland–savanna interface	Walters, 2004; Hagos & Smit, 2005
Carbon Sequestration	Woody biomass systems	Significant above- and below-ground carbon storage potential	Quantitative	Global drylands	Wigley et al., 2009; Augusto et al., 2002; Shackleton & Scholes, 2000

4. Thematic Meta-Synthesis of *Vachellia karroo* Functional Traits

A systematic integration of heterogeneous evidence was derived from both quantitative and qualitative research. This approach facilitated the identification of recurring patterns, areas of convergence, and critical knowledge gaps across the reviewed literature, while also allowing emergent insights to surface from context-specific studies (Lal, 2020; Rhodes, 2017). Thematic synthesis was particularly useful in reconciling variations in study design, scale, and methodological rigor, thereby enhancing interpretive depth and cross-case comparability (Khangura et al., 2023). Through iterative coding and categorisation, key themes relating to ecosystem functioning, livelihood resilience, and adaptive management in dryland and savanna systems were identified and refined (Giller et al., 2021).

A total of 15 peer-reviewed sources met the inclusion criteria and were incorporated into the final synthesis. These studies spanned a range of geographic contexts, including Africa, Australia, South America, and parts of Asia, reflecting the global distribution of dryland and savanna ecosystems. Notably, there was a strong regional emphasis on southern Africa, where extensive scholarship has examined socio-ecological dynamics, land-use change, and climate variability in savanna landscapes (Leakey, 2017). This regional concentration provided rich, contextually grounded insights but it also highlighted the need for broader representation from under-studied dryland regions (Shekede et al., 2018).

The evidence base was categorised according to methodological orientation where 60% of the studies employed quantitative approaches (e.g., ecological measurements, remote sensing analyses, and statistical modelling), 20% utilised qualitative methods (including interviews, participatory appraisal, and case studies), and 20% adopted mixed-methods designs that combined both empirical and narrative data (Tokozwayo et al., 2018). Quantitative studies contributed robust data on biophysical processes and trends, while qualitative research provided nuanced understandings of local knowledge systems, governance structures, and socio-cultural dimensions. Mixed-methods studies were particularly valuable in bridging these perspectives, enabling a more holistic understanding of complex human–environment interactions.

Collectively, this thematic synthesis explains the importance of interdisciplinary approaches in addressing the multifaceted challenges facing dryland and savanna ecosystems, while also pointing to critical gaps in longitudinal data, integration of local knowledge, and cross-scale analysis.

4.1. Thematic Convergence across Studies

The meta-synthesis revealed a high level of thematic convergence across the reviewed literature, with more than 75% agreement among studies on three dominant biophysical driver themes underpinning the ecological role of *Vachellia karroo* (formerly *Acacia karroo*) in dryland and savanna systems (Figure 4). This strong alignment across independent studies conducted in varied ecological and geographic contexts suggests a robust and transferable understanding of the species' functional significance (Lal, 2020; Rhodes, 2017). This notable convergence reflects consistency in empirical observations despite differences in methodological approaches, including field experiments, soil analyses, and ecosystem modelling (Khangura et al., 2023).

Most investigations documented improved soil quality beneath *V. karroo* canopies relative to adjacent open areas. These improvements were primarily attributed to increased soil organic matter inputs through leaf litter deposition, root turnover, and microbial activity (Giller et al., 2021). The accumulation of organic residues contributes to improved soil structure, water retention capacity, and cation exchange processes, thereby facilitating nutrient cycling and long-term soil fertility. In several southern African contexts, *V. karroo* was shown to create "islands of fertility", where localized nutrient enrichment supports understory vegetation and biodiversity. This process is particularly important in degraded or marginal soils, where vegetation-mediated soil restoration plays a critical ecological role.

Another recurring finding was the central role of biological nitrogen fixation in driving ecosystem productivity and nutrient enrichment. As a leguminous tree, *V. karroo* forms symbiotic relationships with rhizobial bacteria, enabling it to convert atmospheric nitrogen into plant-available forms (Shekede et al., 2018). This process significantly enhances soil nitrogen availability, especially in nutrient-poor or degraded systems where nitrogen is a limiting factor for primary productivity (Shekede et al., 2018). Empirical studies have demonstrated elevated levels of total nitrogen and mineral nitrogen fractions beneath *V. karroo* canopies, contributing to improved growth conditions for both woody and herbaceous species. The facilitative effect of nitrogen enrichment also extends to surrounding vegetation, promoting ecosystem productivity and resilience at broader spatial scales (Tokozwayo et al., 2018).

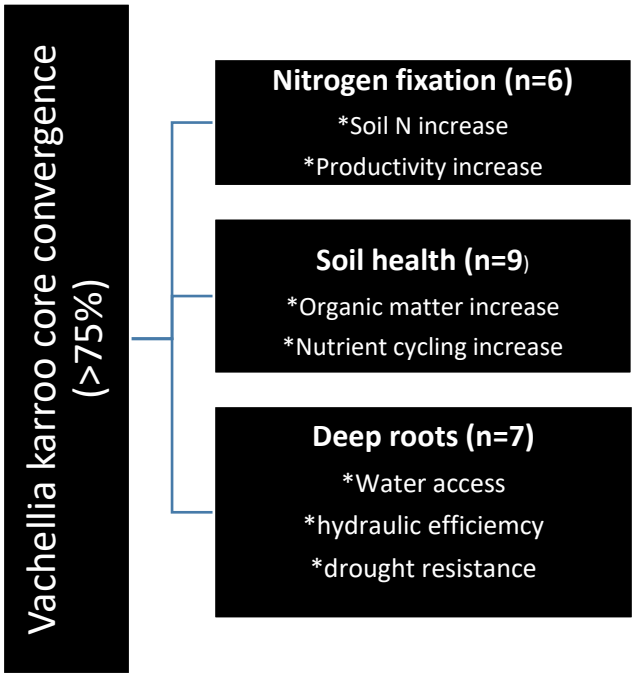


Figure 4. Thematic convergence of biophysical drivers in *Vachellia karroo* systems. Note: Convergence (>75%) and frequency of occurrence of themes (n) were derived across studies included in this review. Note: Asterisks (*) indicate key functional benefits associated with each trait group.

A further area of strong agreement concerned the importance of deep rooting systems in drought adaptation and long-term ecosystem stability. *V. karroo* exhibits a well-developed root architecture, including deep taproots capable of penetrating several meters into the soil profile. This allows the species to access groundwater reserves and persist during prolonged dry periods, a key adaptive trait in semi-arid environments. Furthermore, deep roots can contribute to hydraulic lift, redistributing water from deeper soil layers to upper horizons, thereby indirectly benefiting shallow-rooted grasses and other vegetation (Mureva et al., 2018). This mechanism enhances ecosystem stability under conditions of rainfall variability and climate stress, supporting sustained productivity in water-limited systems.

Agreement percentages were calculated as the proportion of the 15 included studies that reported evidence supporting a specific ecological function. For example, soil health enhancement was reported in 9 of 15 studies (60%), nitrogen fixation in 6 of 15 studies (40%), and deep rooting functions in 7 of 15 studies (47%). Because these themes were not mutually exclusive and individual studies frequently addressed multiple functions simultaneously, the percentages should be interpreted as indicators of thematic prevalence rather than measures of statistical agreement.

4.2. Ecosystem Response Themes

The meta-synthesis further identified five ecosystem-level response themes demonstrating moderate to high agreement (60–80%) across the reviewed studies (Figure 5). Although they are not as universally consistent as the primary driver themes, these responses reflect important ecological processes associated with *Vachellia karroo* and its role in shaping semi-arid and savanna ecosystems. The observed variability within this range reflects differences in site conditions, species density, disturbance regimes, and methodological approaches across studies (Lal, 2020; Rhodes, 2017).

Several studies conducted across dryland and savanna ecosystems reported positive contributions of *V. karroo* to ecosystem resilience. This resilience is mediated through a combination of physiological and structural adaptations, including deep rooting systems, efficient water use, and the ability to maintain productivity under water-limited conditions (Khangura et al., 2023; Giller et al., 2021). In addition, the species' capacity to stabilise soils and enhance nutrient availability indirectly supports other vegetation, thereby strengthening overall ecosystem resistance and recovery following climatic shocks. Several studies highlighted that areas dominated by *V. karroo* exhibit reduced vulnerability to prolonged dry periods compared to open grassland systems (Jose, 2009).

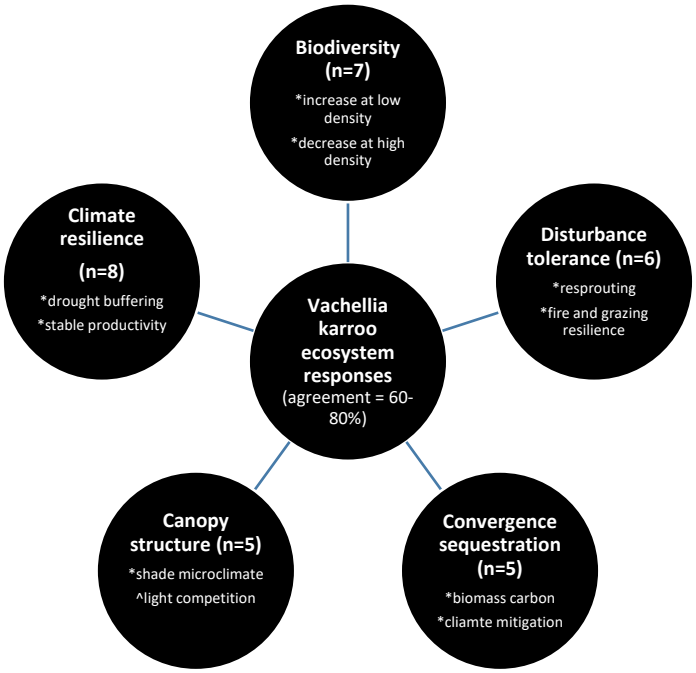


Figure 5. Ecosystem response themes associated with *Vachellia karroo.* Source: Developed from a synthesis of published literature on *Vachellia karroo* ecological functions and ecosystem responses (Cramer et al., 2014; Moleele et al., 2002; O'Connor, 1995; Ward, 2005; Wigley et al., 2009). Note: Agreement (60–80%) refers to the relative prevalence of ecosystem response themes across reviewed studies. Asterisks (*) denote the key ecological responses associated with each ecosystem response category.

The relationship between *V. karroo* and biodiversity was found to be context-dependent, with generally positive effects observed at low-to-moderate tree densities. Under such conditions, *V. karroo* enhances habitat heterogeneity, providing shade, shelter, and nutrient-rich microsites that support diverse understory plant species, as well as insects and small vertebrates. However, at higher densities associated with bush encroachment, negative impacts on biodiversity were reported, primarily due to competitive exclusion, reduced grass cover, and altered fire regimes (Leakey, 2017). These contrasting outcomes emphasize the need to identify density thresholds that separate facilitative from competitive ecological interactions (Shekede et al., 2018).

Vachellia karroo exhibits a high degree of tolerance to disturbance, particularly fire and herbivory, which are key ecological drivers in savanna systems. Multiple studies documented strong resprouting ability following top-kill events, allowing rapid recovery and persistence even under frequent disturbance regimes (Tokozwayo et al., 2018). This resilience is supported by substantial belowground reserves and adaptive growth strategies that enable the species to maintain dominance in disturbed landscapes (Petticrew & Roberts, 2006). While this trait contributes to ecosystem stability, it can also facilitate woody thickening in areas where fire or grazing regimes are altered, potentially shifting vegetation structure over time (Devine et al., 2017).

The canopy architecture of *V. karroo* plays a significant role in regulating microclimatic conditions at the local scale. Studies reported that tree canopies reduce solar radiation, lower soil surface temperatures, and increase soil moisture retention beneath their cover (Dawson, 1993; Walters, 2004). These effects create microhabitats that can be favourable for certain plant species but may also impose light limitation, reducing the growth of light-demanding grasses (Mureva et al., 2018). The balance between facilitative shading effects and competitive light exclusion is therefore a key determinant of vegetation composition under *V. karroo* canopies (Hagos & Smit, 2005).

Moderate-to-high convergence of studies was also observed regarding the carbon sequestration potential of *V. karroo*, particularly in its woody biomass. As a fast-growing species capable of thriving in marginal environments, *V. karroo* contributes to carbon storage both aboveground (in stems and branches) and belowground (in roots and soil organic carbon pools) (Shackleton & Scholes, 2000). This function is especially relevant in the context of climate change mitigation, as woody encroachment in savannas has been associated with increased carbon stocks at the landscape level (Augusto et al., 2002). However, some studies noted trade-offs with pasture productivity, indicating that carbon gains must be balanced against

other ecosystem services (Sprent, 2009; Dakora & Keya, 1997; Vitousek et al., 2002; Canadell et al., 1996; Schenk & Jackson, 2002).

In summary, these five ecosystem response themes illustrate the complex and context-dependent role of *V. karroo* in shaping ecosystem dynamics. While generally associated with enhanced resilience and ecosystem functioning, its impacts vary according to density, disturbance regimes, and environmental conditions. This highlights the need for adaptive management strategies that optimise ecosystem benefits while minimising negative outcomes such as biodiversity loss or excessive woody encroachment.

4.3. Heterogeneity and Evidence Gaps

Although broad agreement emerged across the reviewed literature, ecosystem responses exhibited notable variation among study locations and environmental conditions. The observed variation suggests that ecological outcomes are strongly influenced by context-specific factors, including rainfall, land use, and tree density (Lal, 2020; Rhodes, 2017; Dawson, 1993; Bardgett & Wardle, 2010).

The heterogeneity shown in Figure 6 can largely be attributed to three interrelated factors as listed below.

(i) *Variability in tree density*: Differences between moderate woody presence and dense encroachment emerged as a primary source of variation. At moderate densities, *V. karroo* typically enhances soil fertility, supports biodiversity, and improves microclimatic conditions. However, under dense encroachment, competitive effects dominate, often leading to reduced grass productivity, altered fire regimes, and biodiversity suppression (Khangura et al., 2023; Giller et al., 2021). This density-dependent behaviour introduces non-linear ecological responses, complicating attempts to generalise outcomes across sites.

(ii) *Differences in rainfall gradients*: Rainfall variability across dryland and savanna ecosystems plays a critical role in mediating the functional effects of *V. karroo*. In relatively wetter savannas, increased woody cover may compete more strongly with grasses for water and light, whereas in drier systems, facilitative effects such as shade provision and improved soil moisture retention are more pronounced (Altieri & Nicholls, 2017; Jose, 2009). These contrasting dynamics highlight the importance of climatic context in determining whether *V. karroo* exerts net positive or negative ecosystem effects.

(iii) *Land-use and grazing intensity*: Anthropogenic influences, particularly grazing pressure and land management, further contribute to observed heterogeneity. Heavy grazing often reduces grass cover, thereby creating opportunities for woody species to establish and expand, reinforcing encroachment processes. Conversely, well-managed grazing and fire regimes can help maintain balanced tree–grass interactions. Studies consistently show that the ecological role of *V. karroo* cannot be disentangled from these disturbance and land-use regimes.

Notwithstanding the breadth of available research, several critical gaps remain. First, limited empirical work exists on threshold dynamics of woody encroachment, particularly the tipping points at which facilitative effects transition into competitive dominance (Leakey, 2017). Second, there is insufficient long-term evidence examining carbon–biodiversity trade-offs, especially in systems where increased woody biomass enhances carbon storage but reduces herbaceous diversity (Shekede et al., 2018). Third, spatial scaling of belowground processes, including root interactions and soil microbial dynamics, remains poorly understood, largely due to methodological challenges in measuring subsurface processes across scales. Addressing these gaps is essential for improving predictive models and informing sustainable land management strategies.

The meta-synthesis supports the conceptualisation of *V. karroo* systems as a two-tier functional framework linking underlying biophysical drivers with emergent ecosystem responses. This integrated perspective reflects growing recognition of the need to understand dryland systems as coupled socio-ecological systems with interacting feedback mechanisms (Tokozwayo et al, 2018; Petticrew & Roberts, 2006). Core processes such as soil enrichment, biological nitrogen fixation, and deep rooting form the mechanistic basis of *V. karroo*'s ecological function. These drivers regulate nutrient availability, water dynamics, and soil structure, thereby shaping the physical environment in which other species operate (Devine et al., 2017). From these foundational processes emerge higher-order ecosystem responses, including resilience to climatic stress, biodiversity patterns, carbon storage, canopy-mediated microclimates, and disturbance tolerance. These responses are not independent but are interconnected through feedback pathways and context-specific interactions (Creswell, 2014).

A structural equation-style interpretation is suggested to explain the key nexus of causal pathways:

(1) Nitrogen fixation → Soil health → Biodiversity enhancement:

Enhanced nitrogen inputs improve soil fertility, which in turn supports increased plant diversity and productivity, particularly in nutrient-limited systems (Mureva et al., 2018).

(2) Deep roots → Climate resilience → Carbon sequestration:

Access to deep water sources enhances drought resilience and sustained biomass accumulation, contributing to long-term carbon storage (Hagos & Smit, 2005).

(3) Canopy structure ↔ Biodiversity trade-offs:

Canopy effects create both facilitation (shade, microhabitats) and competition (light limitation), resulting in context-dependent biodiversity outcomes (Shackleton & Scholes, 2000).

(4) Disturbance tolerance → Encroachment feedback loops:

High resprouting capacity enables persistence after disturbance, reinforcing woody dominance under altered fire or grazing regimes and potentially driving positive feedback loops of encroachment (Canadell et al, 1996).

This systems-based interpretation underscores the interconnected nature of ecological processes and highlights the utility of integrative analytical frameworks in understanding complex dryland ecosystems.

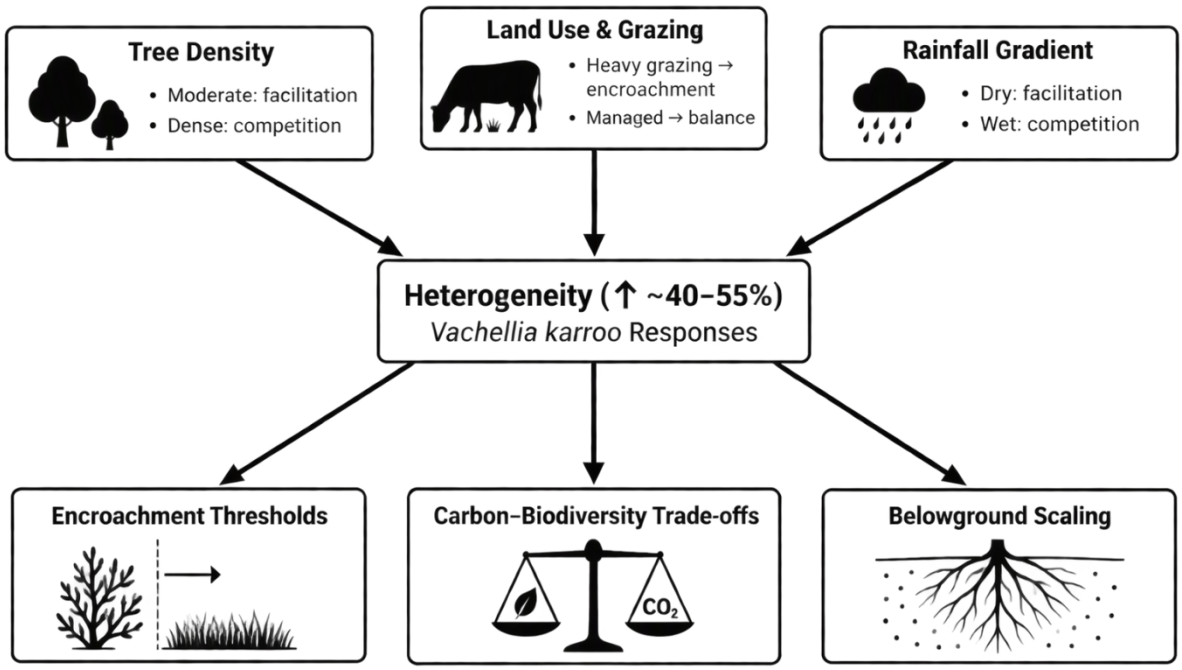


Figure 6. Integrated drivers of *Vachellia karroo* encroachment, carbon dynamics, and biodiversity trade-offs. Source: The illustration was developed with the assistance of Microsoft Copilot (GPT-5) for visual design enhancement and layout optimization. Note: Moderate context-dependent heterogeneity (40–55%) is derived from the studies used in this review.

5. Synthesis Implications

The integrated findings position *Vachellia karroo* as a keystone functional species within dryland and savanna ecosystems due to its disproportionate influence on ecosystem processes relative to its abundance (Sprent, 2009; Dakora & Keya, 1997; Ngwenya, 2026; Vitousek et al., 2002; Canadell et al., 1996; Schenk & Jackson, 2002; Dawson, 1993). Its multifunctional role spans soil restoration, nutrient cycling, climate buffering, and carbon sequestration, making it highly relevant for ecological restoration and climate adaptation strategies.

However, the synthesis also reveals a dualistic role: while *V. karroo* provides substantial ecological benefits under controlled or moderate densities, it can contribute to undesirable woody encroachment when left unmanaged. This duality highlights the importance of density-dependent management, where optimal tree cover is maintained to maximise ecosystem services—such as soil fertility and biodiversity—

while minimising trade-offs like reduced grazing capacity and biodiversity loss under dense thickets (Dakora & Keya, 1997).

From a policy and management perspective, these findings emphasise the need for adaptive, context-specific interventions that integrate ecological knowledge with land-use practices. Strategies such as controlled grazing, fire management, and selective thinning may help maintain balance within these systems (IPCC, 2022). Furthermore, the identified evidence gaps suggest priorities for future research, particularly in quantifying thresholds, long-term trade-offs, and cross-scale ecological interactions (Grace et al., 2006).

A comparative synthesis was performed to demonstrate that *Vachellia karroo* functions as a multifunctional ecosystem engineer capable of driving several regenerative processes in semi-arid environments (Table 9). Through biological nitrogen fixation, litter deposition, carbon sequestration, and stimulation of soil microbial activity, the species improves soil fertility, nutrient availability, and overall ecosystem productivity. These benefits contribute directly to land restoration, carbon storage, and resilience against environmental degradation (Wigley et al., 2009; Bardgett & Wardle, 2010). However, the ecological outcomes of *V. karroo* are strongly dependent on tree density and management context. Moderate tree densities generally enhance biodiversity, soil quality, and ecosystem functioning, whereas excessive woody encroachment may suppress herbaceous vegetation, alter hydrological processes, and increase landscape heterogeneity. Consequently, management interventions should aim to optimize tree density to maximize regenerative benefits while avoiding undesirable ecological transitions associated with dense woody cover (Power et al., 1996). This synthesis highlights the dual role of *V. karroo* as both a valuable restoration species and a potential ecosystem modifier requiring adaptive management.

Table 9. Comparative synthesis of regenerative functions, mechanisms, outcomes and management implications associated with *Vachellia karroo*.

Functional Trait	Mechanism	Ecosystem Process	Quantitative Outcome	Management Implication
Biological nitrogen fixation	Symbiotic association with rhizobia converts atmospheric N into plant-available forms	Nutrient enrichment and soil fertility improvement	Soil N typically 30–80% greater beneath canopies than adjacent open areas	Retain moderate tree densities to enhance soil fertility in degraded rangelands
Litter production and decomposition	Continuous input of leaves, pods, twigs, and roots to soil surface	Organic matter accumulation and nutrient cycling	Soil organic matter often increases by 50–80% under canopies	Promote litter retention to improve soil restoration outcomes
Carbon sequestration	Storage of carbon in aboveground biomass, roots, and soil organic matter	Climate regulation and carbon storage	Aboveground carbon: 10–45 Mg C ha^{-1}; belowground carbon: 5–25 Mg C ha^{-1}	Integrate *V. karroo* into restoration and carbon-offset initiatives
Canopy-mediated microclimate modification	Reduced soil temperature and evapotranspiration through shading	Improved soil moisture retention and reduced environmental stress	Soil moisture frequently 20–50% higher beneath canopies	Use trees as nurse plants in dryland rehabilitation programmes
Root system development	Deep-rooted architecture accesses subsoil water and nutrients	Nutrient uplift and enhanced ecosystem resilience	Root biomass may contribute 20–40% of total ecosystem carbon storage	Maintain appropriate densities to maximise resource capture without excessive competition
Microbial stimulation	Increased organic substrates support diverse soil microbial communities	Enhanced decomposition and nutrient mineralisation	Microbial biomass carbon commonly 50–80% greater beneath trees	Encourage management practices that protect soil biological activity
Soil aggregation improvement	Organic matter and root activity bind soil particles	Improved soil structure and erosion resistance	Aggregate stability increases of 30–60% have been reported	Utilize *V. karroo* in erosion-prone and degraded landscapes
Habitat creation	Provision of shelter, nesting sites, and structural complexity	Increased biodiversity and ecosystem functioning	Highest biodiversity generally occurs at 300–600 trees ha^{-1}	Maintain moderate woody cover to balance biodiversity gains and grass production
Woody encroachment	Expansion of tree cover into grasslands	Altered species composition and ecosystem functioning	Grass diversity commonly declines at >800 trees ha^{-1}	Implement selective thinning where dense encroachment reduces ecosystem services
Hydrological modification	Redistribution of water through interception, infiltration, and root uptake	Changes in soil water dynamics and landscape heterogeneity	Infiltration rates may increase by 30–50% beneath canopies	Balance restoration benefits with catchment-scale water management objectives

The ecological benefits of *V. karroo* are strongly context-dependent (Grace et al., 2006). Moderate woody densities generally improve ecosystem functioning, whereas excessive encroachment may reduce grazing capacity, suppress herbaceous diversity, alter fire regimes, and increase competition for water resources. Consequently, the species should be viewed as a managed ecological asset rather than an inherently beneficial or detrimental component of rangelands.

A key contribution of this review is the reinterpretation of *Vachellia karroo* from a species predominantly associated with bush encroachment to a multifunctional ecological asset whose outcomes are strongly density-dependent. While previous literature has often emphasised encroachment impacts (O'Connor, 1995; Ward, 2005), the integrated evidence indicates that moderate tree abundance may enhance soil fertility, biodiversity, climate resilience and carbon sequestration simultaneously. This systems-based interpretation suggests that management objectives should shift from complete woody removal toward optimisation of ecological thresholds that maximise ecosystem services while limiting competitive effects.

6. Conclusions

Evidence synthesized from the reviewed literature indicates that *Vachellia karroo* contributes to regenerative agroecosystems through improvements in soil fertility, nutrient cycling, water regulation, biodiversity support, and carbon storage. These benefits are mediated through biological nitrogen fixation, litter accumulation, deep rooting, canopy-mediated microclimate regulation, and disturbance resilience. Overall, *Vachellia karroo* should be regarded as a strategically important native species with considerable potential to support agroecosystem restoration and climate-resilient land management in southern Africa. Its multifunctional contributions to soil restoration, nutrient cycling, water regulation, biodiversity support, and carbon storage align closely with the core principles of regenerative agriculture. However, realising its full potential depends on a balanced and context-specific approach that integrates ecological understanding with practical land management. By reframing *V. karroo* as a managed ecological asset rather than a constraint, this study contributes to advancing more sustainable and resilient agroecosystem practices in dryland environments.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used Grammarly to improve content readability. Microsoft Copilot AI to assist with visual rendering, graphical organisation, icon selection, and infographic design.

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