ENVIRONMENTAL REPORTS
Review Article
ISSN: 3041-556X
Journal homepage: https://er.researchfloor.org/

Sacred Groves as Natural Regulators: Reviewing the Ecological Functions and Ecosystem Services of Karnataka's Devara Kadu

Meghana Nayak, and T. S. Harsha*

Department of Environmental Science, KSOU, Mysore, India

Citation: Meghana Nayak, and T. S. Harsha (2026). Sacred Groves as Natural Regulators: Reviewing the Ecological Functions and Ecosystem Services of Karnataka's Devara Kadu. *Environmental Reports; an International Journal*.
DOI: https://doi.org/10.51470/ER.2026.8.1.201

Corresponding Author: **T. S. Harsha** | E-Mail: **(raoamer@gmail.com)**

Received 09 February 2026 | Revised 13 March 2026 | Accepted 11 April 2026 | Available Online May 10 2026

ABSTRACT

Sacred groves, locally known as Devara Kadu in Karnataka, represent one of the oldest forms of community-based forest conservation, safeguarded through traditional beliefs, cultural values, and customary practices. These ecologically significant forest patches serve as natural regulators of environmental processes while providing a wide range of ecosystem services essential for ecological sustainability and human well-being. This review synthesizes existing literature on the ecological functions and ecosystem services of Karnataka's sacred groves, drawing on studies of biodiversity, soil science, hydrology, biogeochemistry, microbiology, and traditional ecological knowledge. Sacred groves exhibit multi-layered vegetation, continuous litter inputs, substantial soil organic carbon stocks, and relatively undisturbed soil conditions that collectively support biogeochemical cycling, biological regulation, and physico-chemical environmental modulation. The review highlights their role in biodiversity conservation, climate regulation, hydrological balance, soil conservation, nutrient cycling, carbon sequestration, and habitat connectivity, and examines their contribution to the conservation of endemic, rare, threatened, and medicinal plant species, as well as pollinators, wildlife, and microbial diversity. Sacred groves function as dynamic social-ecological systems that regulate key ecosystem processes through the interaction of vegetation, soils, microorganisms, hydrology, and long-term cultural stewardship. Significant knowledge gaps remain, particularly regarding direct process-based measurements of carbon sequestration rates, groundwater recharge, pollination effectiveness, and microbial community function. Future research should prioritize interdisciplinary, process-based studies to quantify ecosystem functions and strengthen the integration of sacred groves into conservation policies, restoration programmes, and climate adaptation strategies.

Keywords: *Devara Kadu; sacred groves; ecosystem services; biogeochemical cycling; Western Ghats; Karnataka; community-based conservation; bio-regulation.*

1.0 Introduction

Across India, numerous patches of forest have survived for centuries not because of formal conservation policies, but because of cultural traditions, religious beliefs, and community stewardship. These forests, commonly known as sacred groves, represent one of the oldest forms of community-based conservation and continue to serve as important reservoirs of both biological and cultural diversity. Gadgil and Vartak [8] described sacred groves as relic patches of natural vegetation protected through religious beliefs and customary institutions, noting that they harbour vegetation in its climax formation and probably constitute the only representation of forests in a near-virgin condition in many parts of present-day India. In Karnataka, particularly in the Western Ghats and Kodagu region, sacred groves are known as *Devara Kadu* and have historically been preserved through traditions linked to local deities and long-standing community protection [13].

The ecological importance of sacred groves has been recognized in numerous studies, particularly in relation to biodiversity conservation and ethnobotanical resources [4,5]. Many groves support rare, endemic, and medicinal plant species and often act as refuges for native flora and fauna within landscapes that have undergone extensive agricultural or developmental change. As a result, research on sacred groves has largely focused on documenting species diversity, traditional ecological knowledge, and their role in conserving biological heritage.

However, ecosystems provide far more than habitat for species. Through interactions among vegetation, soils, microorganisms, water, and climate, ecosystems regulate a range of processes that are essential for environmental stability. These include nutrient cycling, carbon storage, hydrological regulation, pollination, soil formation, and the moderation of local climatic conditions. Such processes are collectively categorized as regulating ecosystem services [15].

Although the biodiversity value of sacred groves is well established, considerably less attention has been directed toward understanding how these ecosystems regulate ecological processes. Existing studies often document structural characteristics such as vegetation composition, litter accumulation, and soil properties, yet the implications of these features for ecosystem regulation have received comparatively limited synthesis. As a result, the role of sacred groves in biogeochemical cycling, biological regulation, and physico-chemical environmental regulation remains less clearly understood than their contribution to biodiversity conservation.

This review examines available evidence regarding the regulatory functions of sacred groves, with particular emphasis on the *Devara Kadu* systems of Karnataka. By bringing together findings from studies on vegetation, soils, ecosystem processes, and ecological interactions, the review evaluates the extent to which sacred groves can be viewed as active bio-regulators and identifies key areas where further research is needed.

2.0 Structural and ecological characteristics of sacred groves

Sacred groves are often regarded as remnants of natural vegetation that have persisted within increasingly modified landscapes because of long-standing cultural protection. In many regions, they represent some of the few surviving examples of forest communities that once occupied larger areas before agricultural expansion and land-use change. Gadgil and Vartak [8] suggested that these groves function as ecological relics, preserving elements of native vegetation that have disappeared from much of the surrounding landscape.

One of the most distinctive features of sacred groves is their structural complexity. Unlike many managed ecosystems, sacred groves frequently retain multilayered vegetation composed of canopy trees, understory species, shrubs, climbers, and herbaceous plants. This vertical stratification creates a variety of microhabitats and contributes to habitat heterogeneity, supporting diverse ecological interactions among plants, animals, and microorganisms.

Several studies from the Western Ghats have documented high levels of plant diversity within sacred groves, including endemic, rare, and medicinally important species. In Kodagu, Boraiah et al. [5] reported greater medicinal plant richness and regeneration within sacred groves than in nearby reserve forests, with sacred groves found to shelter nearly twice the density of medicinal plant species compared with state-managed forests. Such findings suggest that cultural protection has allowed these forest patches to maintain ecological conditions favourable for species persistence and natural regeneration. The ecological functioning of sacred groves is closely linked to soil processes. Continuous deposition of leaf litter, twigs, flowers, and other plant material contributes to the accumulation of organic matter on the forest floor. This organic layer supports decomposition and nutrient turnover while helping maintain soil fertility. Rajendraprasad et al. [18] emphasized the importance of litter dynamics in sustaining nutrient cycling within sacred grove ecosystems. Similarly, Hangarge et al. [11] reported substantial soil organic carbon stocks associated with dense vegetation cover, persistent litter accumulation, and relatively low levels of disturbance.

Beneath the forest floor, soil microorganisms play a crucial role in maintaining ecosystem processes. Through decomposition and nutrient transformation, microbial communities facilitate the recycling of organic matter and contribute to nutrient availability for plants. Although relatively few studies have examined microbial diversity directly within sacred groves, broader ecological research indicates that undisturbed forest soils typically support diverse and active microbial communities that enhance ecosystem stability and productivity.

Comparisons between sacred groves and surrounding land-use systems often reveal notable ecological differences. Higher plant diversity, greater structural complexity, and stronger evidence of natural regeneration have been reported in sacred groves than in adjacent agricultural areas, plantations, or other disturbed habitats [3,5].

These characteristics suggest that sacred groves retain ecological functions that may be diminished elsewhere in the landscape.

At the same time, sacred groves are not ecologically uniform. Their condition varies according to factors such as size, degree of isolation, disturbance history, and surrounding land use. Smaller or fragmented groves may be more vulnerable to edge effects, invasive species encroachment, and changes in microclimatic conditions. Consequently, the ecological integrity of sacred groves exists along a continuum rather than representing a single, consistent condition across all sites.

Taken together, existing studies show that sacred groves possess a combination of structural and ecological characteristics that distinguish them from many surrounding managed landscapes. Their multilayered vegetation, continuous litter inputs, and relatively undisturbed soils create conditions that support biodiversity conservation and ecosystem functioning. While these structural attributes have been documented extensively, the ecological processes arising from them have received less attention. Understanding how these features contribute to ecosystem regulation is therefore essential for evaluating the broader ecological significance of sacred groves.

3.0 Regulation of biogeochemical cycles

The ecological significance of sacred groves extends beyond the species they contain. Their mature vegetation, accumulated organic matter, and relatively undisturbed soils create conditions that influence the movement and transformation of carbon, nutrients, and water. These processes form the foundation of ecosystem functioning and contribute to productivity, environmental stability, and resilience across landscapes.

3.1 Carbon sequestration and climate regulation

Forested ecosystems are important components of the global carbon cycle because they remove carbon dioxide from the atmosphere and store it in vegetation, litter, and soils. Sacred groves share many of the characteristics commonly associated with effective carbon storage, including mature tree populations, dense vegetation cover, and long periods of protection from anthropogenic disturbance.

Evidence from the Western Ghats suggests that sacred groves can function as significant carbon reservoirs. Hangarge et al. [11] reported substantial soil organic carbon stocks within sacred grove ecosystems, linking them to continuous litter accumulation and relatively stable soil conditions. In addition to soil carbon, mature trees contribute to aboveground biomass storage, potentially allowing sacred groves to retain carbon pools that have been reduced or lost in surrounding agricultural and plantation landscapes.

The influence of vegetation extends beyond carbon storage alone. Forest canopies affect local climatic conditions through shading, evapotranspiration, and moisture regulation-processes that can moderate temperature and influence local energy balances.

Nevertheless, relatively few studies have directly quantified aboveground biomass carbon, long-term sequestration rates, or the broader climatic effects of sacred groves. Current evidence therefore supports their role in carbon storage, but the magnitude of their contribution to climate regulation remains insufficiently quantified.

(Photo by Raksha S, multi-layered canopy at Katthale Kaanu)

3.2 Nutrient cycling and soil fertility regulation

The cycling of nutrients within ecosystems depends on continuous interactions among vegetation, litter, soil organisms, and microbial communities. In sacred groves, the steady accumulation of leaf litter, twigs, flowers, and other organic materials provides the raw material for decomposition and nutrient recycling. Rajendraprasad et al. [18] emphasized the importance of litter dynamics in sustaining nutrient cycling processes within sacred groves. As organic matter decomposes, nutrients are released and made available for plant uptake, helping maintain ecosystem productivity. Microbial communities play a central role in this process by transforming nutrients into biologically accessible forms, while mycorrhizal fungi enhance nutrient acquisition through symbiotic relationships with plant roots.

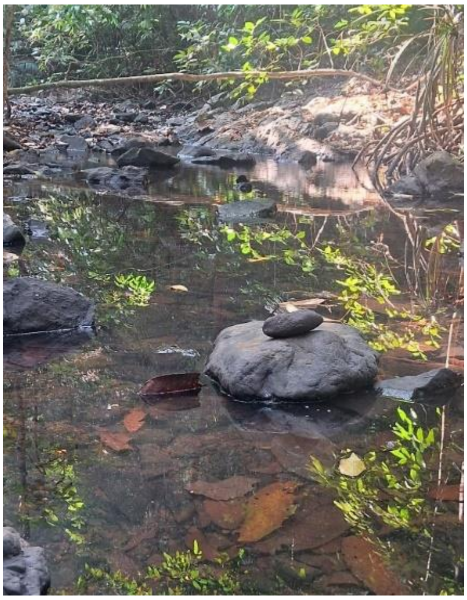
The substantial organic matter commonly observed in sacred grove soils suggests efficient nutrient retention and reduced nutrient loss compared with more heavily disturbed ecosystems. However, much of the current understanding is based on indirect indicators such as litter accumulation, soil organic matter content, and vegetation productivity. Direct measurements of nutrient fluxes, mineralization rates, and nutrient-use efficiency remain limited, making it difficult to quantify the full contribution of sacred groves to nutrient regulation.

3.3 Hydrological regulation and water conservation

Vegetation and soils strongly influence the movement, storage, and availability of water within ecosystems. Through canopy interception, root activity, litter accumulation, and soil stabilization, forests regulate hydrological processes that affect both terrestrial and aquatic environments.

Many sacred groves retain these forest characteristics despite their relatively small size. Dense vegetation cover reduces the impact of rainfall on exposed soil surfaces, while litter layers help slow runoff and increase water retention. Extensive root systems improve soil structure, encourage infiltration, and may contribute to groundwater recharge by facilitating the movement of water into deeper soil layers.

Traditional ecological knowledge frequently associates sacred groves with springs, ponds, and perennial water sources, particularly in the Western Ghats. Such observations are consistent with established principles of forest hydrology and suggest that these forest patches may contribute to local water conservation. Nevertheless, direct measurements of infiltration rates, groundwater recharge, streamflow regulation, and watershed-scale hydrological processes remain scarce. As a result, the hydrological importance of sacred groves is widely recognized but remains inadequately quantified.



(Photo by Raksha S, creek flowing through a wooded area at Katthale Kaanu)

The available literature points to a consistent pattern: sacred groves possess structural features that favour carbon storage, nutrient retention, and hydrological moderation. Mature vegetation, persistent litter inputs, and relatively undisturbed soils create conditions that support these processes. At present, however, much of the evidence is derived from ecological indicators and broader forest ecosystem theory rather than direct process-based measurements. Long-term investigations integrating carbon dynamics, nutrient fluxes, microbial activity, and hydrological monitoring will be essential for developing a more complete understanding of the regulatory functions performed by sacred groves.

4.0 Biological regulation mechanisms

The functioning of ecosystems depends not only on physical and chemical processes but also on interactions among plants, animals, fungi, and microorganisms. Pollination, decomposition, nutrient transformation, biological control, and community interactions all influence ecosystem stability and resilience. Because many sacred groves have experienced relatively low levels of disturbance, they often retain ecological interactions that have been reduced or disrupted in surrounding landscapes. This raises the possibility that sacred groves function not merely as repositories of biodiversity but also as biologically regulated ecosystems.

4.1 Pest and pathogen regulation

Natural ecosystems regulate populations of herbivores and other organisms through complex interactions among predators, parasitoids, pathogens, and host species. Such interactions form the basis of biological control, an important regulating ecosystem service [1].

The structural complexity of sacred groves provides habitat for a wide range of organisms occupying different trophic levels. Diverse plant communities can support equally diverse assemblages of insects, birds, reptiles, and other fauna, creating ecological networks that may contribute to the regulation of herbivore populations. In this context, sacred groves may act as refuges for predators and parasitoids capable of suppressing potential pest species within the grove itself and possibly in surrounding landscapes. Despite the ecological plausibility of this role, empirical evidence remains limited, and the spatial scale over which such effects operate remains largely unknown.

4.2 Pollination services and plant reproduction

Pollination is a critical ecological process that underpins the reproduction of many flowering plants and contributes substantially to agricultural productivity worldwide [14]. Forest fragments often provide nesting sites, food resources, and shelter for pollinators, and sacred groves are likely to perform similar functions. The diverse flowering plants present within sacred groves support a variety of pollinating organisms, including bees, butterflies, moths, birds, and bats. Within fragmented landscapes, these forest patches may serve as refugia that allow pollinator populations to persist despite habitat loss elsewhere. Pollinators associated with sacred groves may also move into adjacent agricultural areas, potentially contributing to crop pollination and broader landscape connectivity. Although these possibilities are supported by ecological theory and observations from comparable ecosystems, direct studies of pollinator diversity, visitation frequency, and pollination effectiveness within sacred groves remain relatively scarce.

4.3 Microbial regulation and nutrient transformation

Among the least visible but most important components of ecosystem regulation are soil microbial communities. Through decomposition, nutrient mineralization, and organic matter turnover, microorganisms play a fundamental role in maintaining ecosystem productivity and nutrient availability [17]. The environmental conditions commonly found in sacred groves are likely to favour microbial activity: thick litter layers provide a continuous source of organic substrates, while relatively stable soil conditions support microbial growth and nutrient transformation. Mycorrhizal fungi further contribute to ecosystem functioning by enhancing nutrient uptake and facilitating plant growth. Despite their ecological importance, microorganisms remain one of the least studied aspects of sacred grove ecology, and current interpretations are therefore based largely on broader knowledge of forest ecosystems. Advances in molecular and microbial ecological techniques may help address this gap in future research.

(Photo by Raksha S, Myristica swamps at Katthale Kaanu)

4.4 Invasion resistance and ecosystem stability

Biological invasions are widely recognized as major drivers of biodiversity loss and ecosystem change. Ecological theory suggests that species-rich communities may be more resistant to invasion because resources are utilized more completely by resident species, leaving fewer opportunities for invaders to establish [7]. Many sacred groves possess characteristics associated with this form of resistance, including high species diversity, multi-layered vegetation, and relatively intact ecological networks. At the same time, invasion resistance should not be viewed as an automatic property of sacred groves. Invasive species have been reported in several disturbed groves, demonstrating that fragmentation, disturbance history, grove size, and landscape context strongly influence ecological outcomes. The capacity of sacred groves to resist invasion therefore varies among sites and cannot be assumed universally. Overall, existing evidence suggests that sacred groves support a range of biological interactions that contribute to ecosystem functioning, including pollination, nutrient transformation, biological control, and the maintenance of community stability. Yet many of these processes remain poorly quantified. Future work that integrates pollination ecology, microbial ecology, trophic interactions, and invasion biology will be necessary to determine how strongly sacred groves influence biological regulation and how these effects vary across landscapes.

5.0 Physico-chemical regulation

Forest ecosystems modify their physical and chemical surroundings through continuous interactions among vegetation, soils, microorganisms, and hydrological processes. These interactions influence local climate, air quality, water movement, and nutrient dynamics, thereby contributing to environmental stability. Sacred groves retain many of the structural features associated with these regulatory functions, including dense vegetation cover, intact litter layers, and relatively undisturbed soils[4][8]. Although direct evidence remains limited in several areas, ecological theory and observations from forest ecosystems suggest that sacred groves may play an important role in shaping local environmental conditions.

5.1 Microclimate buffering

One of the most noticeable effects of forest vegetation is its influence on the local microclimate. By altering radiation balance, evapotranspiration, and airflow, forests often create environmental conditions that differ substantially from those of surrounding open areas [6, 9]. The multi-layered vegetation structure characteristic of many sacred groves is likely to produce similar effects. Dense canopies reduce the amount of solar radiation reaching the forest floor, while evapotranspiration contributes to the maintenance of higher humidity levels. Vegetation can also reduce wind movement, creating a more stable internal environment. Together, these factors may buffer organisms from extreme fluctuations in temperature and moisture. Many qualitative observations describe sacred grove interiors as cooler, moister, and less exposed than adjacent landscapes. However, few studies have systematically measured temperature, humidity, wind speed, or other microclimatic variables within these ecosystems. Detailed field-based assessments would provide valuable insight into the magnitude and ecological significance of these effects.

5.2 Air quality regulation

Vegetation can influence atmospheric quality by intercepting particulate matter and absorbing certain gaseous pollutants. Research conducted in forested and urban green spaces has demonstrated that plant communities can reduce pollutant concentrations and improve local environmental quality [16]. Given their relatively dense vegetation, sacred groves may contribute to similar processes. Tree canopies and understory vegetation increase the surface area available for the capture of airborne particles, while physiological processes may facilitate the uptake of some atmospheric pollutants. Such functions could be particularly relevant where sacred groves occur near settlements, roads, or agricultural areas. Despite this potential, direct measurements of pollutant removal or air-quality improvement within sacred grove ecosystems are currently lacking. The role of sacred groves in atmospheric regulation, therefore, remains largely inferential.

5.3 Water quality regulation

The influence of forests on water quality is well documented. Vegetation cover helps reduce soil erosion, promotes infiltration, retains nutrients, and facilitates the biological transformation of organic materials before they enter aquatic systems [10, 17]. Sacred groves possess many of the ecological characteristics associated with these functions. Dense vegetation protects soils from erosion, root systems enhance infiltration, and litter layers act as natural filters that slow surface runoff and retain suspended materials. In addition, microbial communities contribute to nutrient transformations and decomposition processes that influence water chemistry and nutrient availability. Traditional ecological knowledge frequently links sacred groves with springs, ponds, and perennial water sources, suggesting a long-recognized relationship between these forests and water resources. Although such observations align with established principles of forest hydrology, quantitative studies examining water quality, nutrient retention, sediment dynamics, and watershed processes remain relatively uncommon.

Taken together, existing ecological knowledge suggests that sacred groves possess many of the attributes associated with microclimatic regulation, air-quality improvement, and water-quality maintenance. Dense vegetation, intact litter layers, and minimally disturbed soils provide a strong ecological basis for these functions. Nevertheless, most conclusions currently rely on indirect evidence and ecological inference. Quantitative studies examining microclimate, atmospheric processes, and watershed dynamics are therefore essential for determining the extent to which sacred groves contribute to physico-chemical regulation.

6.0 Sacred groves versus managed ecosystems

The ecological significance of sacred groves becomes particularly evident when they are compared with other land-use systems. Agricultural fields, monoculture plantations, managed forests, and urban green spaces all provide ecosystem services, but they differ markedly in biodiversity, vegetation structure, ecological complexity, and regulatory capacity. Examining these differences helps clarify the role of sacred groves within human-dominated landscapes and provides a broader context for understanding their contribution to ecosystem functioning.

While sacred groves are generally much smaller than extensive natural forests, they often retain structural and ecological characteristics that have been lost from surrounding landscapes. In many regions, they function as islands of ecological complexity embedded within matrices dominated by agriculture, plantations, or urban development. Their importance therefore lies not only in what they conserve internally but also in the ecological functions they sustain within modified environments.

Table 1. Comparison of sacred groves and other managed ecosystems in relation to ecological regulation

Ecological attribute	Sacred groves	Agricultural systems	Monoculture plantations	Urban green spaces	Extensive natural forests
Biodiversity conservation	Often support high species richness, including endemic, rare, and medicinal species; function as ecological refugia [4]	Generally low to moderate diversity due to management for productivity	Moderate diversity but often dominated by a few planted species	Variable; usually lower native biodiversity and greater human influence	Typically highest biodiversity due to large area and habitat continuity
Vegetation structure	Multilayered canopy with trees, shrubs, climbers, and herbs	Simplified structure dominated by crops	Tree cover present but structural complexity often reduced	Usually fragmented and highly managed	Highly complex vegetation structure across multiple strata
Carbon storage	Moderate to high carbon storage owing to mature vegetation and relatively undisturbed soils [11]	Generally low due to cultivation and biomass removal	Moderate carbon storage depending on plantation age and management	Usually limited by size and vegetation density	Highest total carbon stocks due to extensive biomass and soil carbon pools
Hydrological regulation	Promote infiltration, reduce runoff, and may support local water retention	Often associated with increased runoff and soil exposure	Intermediate; hydrological functions depend on management practices	Frequently limited by impervious surfaces and altered drainage	Strong regulation of infiltration, runoff, and watershed processes
Soil quality and nutrient retention	High organic matter, active litter decomposition, and relatively stable soil conditions [18]	Often affected by tillage, erosion, and nutrient depletion	Moderate soil protection but less diverse litter inputs	Frequently disturbed and compacted soils	Typically high organic matter and efficient nutrient cycling
Pollination and biological interactions	Support pollinators, decomposers, predators, and other trophic interactions	Pollination services often depend on surrounding habitats	Reduced interaction diversity compared with natural forests	Can provide habitat for some pollinators but usually at smaller scales	Extensive and highly interconnected ecological networks
Ecological complexity	High ecological complexity relative to their size, supporting multiple trophic levels and ecosystem functions	Simplified ecological networks designed for production	Moderate complexity but lower functional diversity	Variable and often constrained by management	Highest ecological complexity and functional redundancy
Resilience to disturbance	Potentially resilient due to biological diversity and ecological interactions, though influenced by grove size and isolation	Often vulnerable to pests, climate variability, and soil degradation	Susceptible to disease outbreaks and management disturbances	Strongly dependent on human maintenance	Generally high resilience due to scale, diversity, and connectivity

Spatial extent and landscape role	Small but ecologically important patches within human-dominated landscapes	Extensive in agricultural regions but managed primarily for production	Often widespread in production landscapes	Important locally but limited in ecological scope	Large-scale ecosystems regulating regional ecological processes
Overall ecological significance	Function as complementary landscape elements that maintain biodiversity, ecological interactions, and regulating ecosystem services within modified environments	Primarily provide provisioning services	Balance production with limited ecological regulation	Provide localized environmental benefits	Represent the benchmark for long-term ecosystem functioning and regulation

Sources: *Gadgil & Vartak 1976; Boraiah et al. 2003; Bhagwat et al. 2005; Bhagwat & Rutte 2006; Rajendraprasad et al. 2000; Hangarge et al. 2015.*

The comparison highlights an important pattern. Sacred groves frequently retain ecological attributes that are diminished in many managed landscapes, including higher biodiversity, greater structural complexity, richer biological interactions, and more stable soil conditions. These characteristics allow them to support a range of regulating ecosystem services that are often reduced in agricultural systems, monoculture plantations, and urban environments.

At the same time, sacred groves should not be viewed as ecological equivalents of extensive natural forests. Large forests generally support larger populations, more complete ecological networks, broader hydrological functions, and greater total carbon storage. The ecological value of sacred groves therefore, lies in a different capacity: rather than replacing natural forests, they complement them. Within landscapes that have undergone substantial human modification, sacred groves often serve as reservoirs of biodiversity, centres of ecological interaction, and sources of ecosystem regulation. Their contribution is especially important where larger natural forests have been fragmented, degraded, or lost.

7.0 Conservation implications and future directions

The evidence reviewed thus far suggests that sacred groves possess ecological characteristics associated with a wide range of regulatory functions, including carbon storage, nutrient cycling, hydrological moderation, pollination support, biological control, and microclimatic buffering. Sacred groves also provide valuable opportunities to examine how ecological processes are maintained within human-dominated landscapes and how traditional systems of protection contribute to long-term environmental stability.

7.1 Sacred groves as reference systems for ecological restoration

Modern ecological restoration increasingly aims to recover ecosystem functioning and resilience rather than simply re-establish vegetation cover. Sacred groves offer useful insights in this context because many have retained relatively intact vegetation structure, diverse species assemblages, functioning soil systems, and ecological continuity despite extensive alteration of the surrounding landscape. The multilayered vegetation, persistent litter inputs, and relatively undisturbed soils found in many sacred groves illustrate characteristics commonly associated with stable and self-sustaining ecosystems. They can serve as ecological reference systems that help identify structural and functional attributes associated with ecosystem recovery and long-term resilience, particularly in regions where natural forests have been fragmented or degraded.

7.2 Integrating traditional ecological knowledge and scientific monitoring

A defining feature of sacred groves is the close relationship between ecological processes and cultural institutions. Unlike many formally protected areas, the persistence of sacred groves has historically depended on traditional beliefs, customary management practices, and community stewardship [2,8]. This long-standing relationship creates opportunities for integrating traditional ecological knowledge with contemporary scientific approaches. Local communities often possess detailed observations regarding species distributions, seasonal ecological changes, resource use patterns, and environmental fluctuations, accumulated over generations knowledge that can complement ecological monitoring by providing historical and contextual perspectives that short-term scientific studies may not capture. Scientific methods can in turn contribute quantitative assessments of biodiversity, ecosystem functioning, and environmental change. Such integration is increasingly recognized as important for both conservation planning and the management of social-ecological systems.

7.3 Relevance to nature-based solutions

The growing emphasis on nature-based solutions has highlighted the importance of ecosystems in addressing contemporary environmental challenges such as biodiversity loss, climate change, and water insecurity [12]. Many of the ecological attributes associated with sacred groves align closely with this framework. Carbon storage, water regulation, biodiversity conservation, and microclimatic moderation are among the functions frequently associated with sacred grove ecosystems. Understanding how these mechanisms operate may provide useful lessons for restoration projects, community-based conservation initiatives, and broader landscape-management strategies. Nevertheless, caution is warranted when attempting to generalize these functions, since sacred groves vary considerably in size, ecological condition, cultural context, and landscape setting.

7.4 Knowledge gaps and research priorities

Despite increasing recognition of their ecological importance, significant uncertainties remain regarding the mechanisms, magnitude, and spatial extent of ecosystem regulation within sacred groves. One of the most persistent limitations in the literature is the scarcity of direct measurements of ecological processes. Numerous studies have documented biodiversity patterns, vegetation structure, soil properties, and general ecological condition, yet comparatively few have quantified regulatory functions such as carbon sequestration rates, nutrient turnover, groundwater recharge, pollination effectiveness, biological control, or microclimatic buffering. Future research should place greater emphasis on process-based measurements that directly link ecosystem structure with measurable ecological outcomes.

A second limitation concerns the predominance of descriptive studies. Existing research often demonstrates that sacred groves differ ecologically from surrounding landscapes, but the mechanisms responsible for those differences are not always clearly identified. Long-term and experimental studies are needed to determine how vegetation structure, species interactions, soil properties, and microbial communities collectively contribute to ecosystem regulation. Particular attention should be directed toward soil microbial communities, which remain among the least studied components of sacred grove ecosystems. Advances in microbial ecology, metagenomics, and functional analysis now provide opportunities to investigate how microorganisms contribute to decomposition, nutrient cycling, carbon stabilization, and ecosystem resilience.

Another challenge is the predominance of site-specific investigations. Landscape-scale approaches incorporating remote sensing, geographic information systems (GIS), and spatial ecological modelling could help clarify how sacred groves collectively contribute to biodiversity conservation, hydrological regulation, carbon storage, and ecological connectivity across larger regions. Future work would also benefit from stronger interdisciplinary perspectives. Examining sacred groves within a social-ecological systems framework may provide a more realistic understanding of their long-term functioning and conservation value.

8.0 Conclusions

Sacred groves are more than biodiversity refuges they are dynamic social-ecological systems that regulate key ecosystem processes through the interaction of vegetation, soils, microorganisms, hydrology, and long-term cultural stewardship. The evidence reviewed indicates that these ecosystems contribute to carbon sequestration, nutrient cycling, water regulation, soil conservation, microclimatic buffering, and habitat connectivity, although several of these functions require further quantitative validation. The persistence of *Devara Kadu* in Karnataka highlights the vital role of indigenous knowledge and community-based conservation in maintaining ecological resilience. As biodiversity declines and climate-related challenges intensify, these culturally protected forests offer valuable nature-based solutions for sustainable landscape management. Future research should prioritize interdisciplinary, process-based studies to quantify ecosystem functions and strengthen the integration of sacred groves into conservation policies, restoration programmes, and climate adaptation strategies. Protecting these living landscapes is not only essential for preserving biodiversity and cultural heritage but also for enhancing ecosystem resilience and environmental sustainability.

Declarations

List of abbreviations: GIS: Geographic Information System; SOC: Soil Organic Carbon; MEA: Millennium Ecosystem Assessment; IUCN: International Union for Conservation of Nature.

Ethics approval and consent to participate: Not applicable. This article is a review of previously published literature and does not involve collection of primary data from human subjects or animals.

Consent for publication: Not applicable.

Availability of data and materials: Not applicable. This is a review article; no new datasets were generated.

Competing interests: The authors declare no competing interests.

Funding: No specific funding was received for this review.

Acknowledgements: The authors thank the Department of Environmental Science, KSOU, Mysore, for institutional support.

References

1. Altieri MA. 1999. The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems and Environment 74:19–31.
2. Berkes F. 2012. Sacred ecology. 3rd edition. Routledge, New York, USA.
3. Bhagwat SA, Kushalappa CG, Williams PH, Brown ND. 2005. The role of informal protected areas in maintaining biodiversity in the Western Ghats of India. Ecology and Society 10(1):8. [online] URL: http://www.ecologyandsociety.org/vol10/iss1/art8/
4. Bhagwat SA, Rutte C. 2006. Sacred groves: potential for biodiversity management. Frontiers in Ecology and the Environment 4(10):519–524.
5. Boraiah KT, Vasudeva R, Bhagwat SA, Kushalappa CG. 2003. Do informally managed sacred groves have higher richness and regeneration of medicinal plants than state-managed reserve forests? Current Science 84(6):804–808.
6. Chen J, Saunders SC, Crow TR, Naiman RJ, Brosofske KD, Mroz GD, Brookshire BL, Franklin JF. 1999. Microclimate in forest ecosystem and landscape ecology. BioScience 49(4):288–297.
7. Elton CS. 1958. The ecology of invasions by animals and plants. Methuen, London, UK.
8. Gadgil M, Vartak VD. 1976. The sacred groves of Western Ghats in India. Economic Botany 30(2):152–160.
9. Geiger R, Aron RH, Todhunter P. 2009. The climate near the ground. 7th edition. Rowman & Littlefield, Lanham, USA.
10. Hamilton LS, King PN. 1983. Tropical forested watersheds: hydrologic and soils response to major uses or conversions. Westview Press, Boulder, USA.
11. Hangarge LM, Kulkarni DK, Gaikwad VB, Mahajan DM. 2015. Soil organic carbon (SOC) in selected sacred groves from Bhor region of Western Ghats, Maharashtra. Asian Journal of Environmental Science 10(2):166–171.
12. IUCN. 2020. Global standard for nature-based solutions. 1st edition. IUCN, Gland, Switzerland.
13. Kalam MA. 1996. Sacred groves in Kodagu district of Karnataka (South India): a sociohistorical study. Pondy Papers in Social Sciences 21. Institut Français de Pondichéry, Pondicherry, India.
14. Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T. 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B 274(1608):303–313.
15. Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press, Washington DC, USA.
16. Nowak DJ, Crane DE, Stevens JC. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry and Urban Greening 4(3–4):115–123.
17. Paul EA, Clark FE. 1996. Soil microbiology and biochemistry. 2nd edition. Academic Press, San Diego, USA.
18. Rajendraprasad M, Krishnan PN, Pushpangadan P. 2000. Vegetational characterisation and litter dynamics of the sacred groves of Kerala, southwest India. Journal of Tropical Forest Science 12(2):320–335.