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Unveiling The Himalayan Treasures: Exploring Vital Ecosystem Services And Navigating Management Challenges – A Comprehensive Review

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Abstract

The Himalayan ecosystem stands out for its unique, delicate ecology and biodiversity, reflected in its distinct ecosystem services (ESs). While numerous studies have explored Himalayan ecosystems, many have overlooked the ES perspective, lacking a standardized classification system. This study aims to rectify this gap by conducting a systematic literature review, analyzing more than 200 publications, including research articles, bo[1]ok chapters, and published reports. Utilizing statistical analysis through PAST (Paleontological Statistics software), five major clusters were identified, revealing strong correlations among them, with one exception. The review underscores the prevalence of improper management planning as a significant challenge in the Himalayan ecosystem. The study advocates for multifaceted approaches, incorporating appropriate land use plans, legislative frameworks, and increased research. It emphasizes the necessity of developing management frameworks and policies aligned with the socio-economic and ecological context of the Himalayas. The primary challenge identified is the need for comprehensive planning to ensure the sustainable management of ecosystem services. Addressing this, the study calls for strong, long-term collaborations between research organizations, development agencies, and government ministries. Such partnerships will facilitate information sharing, creating a unified platform for the development and implementation of effective land management and development strategies at the grassroots level in the Himalayan region. This holistic approach aims to ensure the continuity of ecosystem services and the long-term viability of the Himalayan ecosystems.

Keywords *Himalayan ecosystem, ecosystem services, management challenges, statistical analysis, land use planning.*

1 Introduction

1.1 The Indian Himalayan Region (IHR)

The Himalayan ecosystem stands as a testament to nature's grandeur, boasting immense ecological diversity that shapes the physical, climatic, and cultural landscapes across its vast

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expanse. This unique region, characterized by its towering mountains, intricate glaciology, and diverse hydrology, encompasses a myriad of ecosystems, ranging from alpine meadows and fertile valleys to high-altitude cold deserts, temperate, tropical, and subtropical forests, grasslands, and glacial lake and river systems. The interplay of elevation, slope, aspect, and microclimates contributes to the extraordinary variety of flora and fauna found in the Himalayas. Central to the understanding of the Himalayan ecosystem is the recognition of its profound impact on the livelihoods and cultural traditions of the diverse human societies residing within its bounds. The region encompasses the IHR, spanning 2,500 kilometers and including the Indus and Brahmaputra River systems, with physiographic features ranging from the southern Siwaliks to the northern Tibetan plateau. The IHR harbors three primary mountain ranges - the Himadri (Greater Himalaya), Himanchal (Lesser Himalaya), and the Siwaliks (Outer Himalaya), each separated by significant geological fault lines.

The IHR covers ten states, namely Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, and Meghalaya, along with partial inclusion of Assam and West Bengal. These regions exhibit a rich tapestry of ecosystems, from the high Himalayan mountains and glaciers in northern Uttarakhand to the wooded lower ranges. The diversity of tree species, ranging from subtropical to alpine zones, signifies the region's ecological richness and biodiversity. The Himalayan woods, as highlighted by Singh and Singh (1992), play a crucial role in meeting local population needs and contributing to environmental conservation. These forests, comprising species like Shorea robusta, Pinus roxburghii, and Quercus spp., provide essential ecosystem services such as moisture conservation, regulation of river flow, and mitigation of downstream erosion. Their significance extends beyond ecological aspects, being deeply intertwined with the well-being and sustenance of both upstream and downstream communities (Bruijnzeel and Bremmer 1989; Singh 2007).

Recognizing the pivotal role of ecosystems in supporting human societies, the concept of ecosystem services (ES) gained prominence in the late 1970s (Go´mez-Baggethun et al. 2010), with notable milestones like the Millennium Ecosystem Assessment (MEA) in 2005. The MEA marked a significant step towards categorizing and understanding ES, emphasizing the need to integrate these services into ecological studies (WCED, 1987). However, a plethora of pre-2005 studies remain unclassified under the ES framework, necessitating a comprehensive literature review to identify major challenges in the Himalayan ecosystem. As the demand for ecosystem services intensifies due to infrastructural development, it becomes imperative to assess their economic value (Costanza and Daily 1992; Daily 1997). Costanza et al. (1997, 1998) estimated the global economic value of ecosystem services, highlighting the substantial contribution of marine and coastal systems, as well as terrestrial ecosystems like forests and wetlands. In the context of the Himalayas, Singh (2007) estimated a value of $1150 per hectare per year for ecosystem services provided by nearby forests, underscoring their economic significance.

However, the burgeoning demand for natural resources, coupled with anthropogenic and climate change factors, poses a threat to the sustainability of Himalayan ecosystems. Unsustainable agricultural practices, overharvesting of fisheries, and the intrusion of non-native species contribute to habitat degradation and pose immediate dangers to the delicate balance of these ecosystems (Ehrlich et al. 1977). This calls for a nuanced understanding of ecosystem services, their valuation, and effective management to ensure the resilience and well-being of both the Himalayan environment and its human inhabitants. In light of these challenges, this study aims to identify Himalayan ecosystem services and elucidate the management challenges faced by this ecologically vital region. By comprehensively analyzing the intricate relationships between the environment, human societies, and ecosystem services, this research seeks to contribute to the sustainable management and conservation of the Himalayan ecosystem.

1.2 Breathtaking Biodiversity in the Himalayas

The Himalayan mountain range, often referred to as the "Abode of Snow," is renowned for its stunning landscapes and unparalleled biodiversity. Spanning across several countries, including India, Nepal, Bhutan, China, and Pakistan, the Himalayas boast a rich tapestry of flora and fauna that has captured the fascination of scientists, researchers, and nature enthusiasts alike. This note explores the diverse aspects of Himalayan biodiversity, focusing on flora and fauna diversity, endangered species and conservation efforts, and the unique adaptations of life forms to the harsh mountain environment.

1.2.1 Flora and Fauna Diversity

The Himalayas exhibit an extraordinary range of plant species due to the varying climatic conditions and altitudinal gradients. The lower foothills are adorned with subtropical vegetation, including sal forests, oak, and rhododendron. As one ascends, temperate forests with conifers like pine, spruce, and fir dominate the landscape. Alpine meadows and shrubs characterize the higher altitudes, giving way to cold desert vegetation at extreme elevations. The region is home to a myriad of flowering plants, with an estimated 18,000 species identified so far. Notable among these is the iconic blue poppy (Meconopsis sp.), a symbol of the Himalayan flora. The diverse range of medicinal plants, herbs, and orchids further contributes to the ecological significance of the region.

The Himalayan ecosystem supports a remarkable diversity of wildlife, ranging from elusive snow leopards and red pandas to vibrant pheasants and elusive butterflies. Iconic species such as the Bengal tiger, Himalayan brown bear, and Himalayan Monal pheasant find their habitat in this unique mountainous region. The numerous rivers and lakes within the Himalayas are inhabited by diverse aquatic life, including the elusive Golden Mahseer and snow trout.

1.2.2 Endangered Species and Conservation Efforts

Despite its natural beauty, the Himalayan region faces numerous conservation challenges, primarily due to habitat destruction, climate change, and poaching. Several species, including the snow leopard, red panda, and Himalayan wolf, are classified as endangered. Conservation efforts have been initiated across the Himalayas to protect these vulnerable species. Various national parks and wildlife sanctuaries, such as Hemis National Park in India and Sagarmatha National Park in Nepal, have been established to safeguard the biodiversity of the region. Collaborative initiatives between neighboring countries aim to strengthen conservation measures and protect the migratory routes of species. Community-based conservation programs involving local communities have gained traction, promoting sustainable practices and minimizing human-wildlife conflict. Additionally, international organizations and NGOs are actively involved in research, awareness campaigns, and habitat restoration projects to preserve the unique biodiversity of the Himalayas.

1.2.3 Unique Adaptations to Harsh Environments

Life in the Himalayas has adapted to extreme conditions, including low oxygen levels, cold temperatures, and steep terrain. Species like the snow leopard have evolved to thrive in high-altitude environments, with adaptations such as thick fur, wide paws for walking on snow, and a well-developed respiratory system. The Himalayan blue sheep, or bharal, showcases remarkable climbing abilities, navigating steep cliffs with ease. Plants, too, have adapted to the challenging conditions, with some developing anti-freeze proteins to survive extreme cold, while others display unique physiological mechanisms to cope with high UV radiation at higher altitudes.

2 Data and Methods

Utilizing a systematic approach, we conducted an extensive literature review on ecosystem services in the Himalayan region. We initiated the search with specific terms such as "Ecosystems Services and Himalaya," followed by subcategories like "Provisioning Ecosystem Services and Himalaya," "Regulating Ecosystem Services and Himalaya," "Supporting Ecosystem Services and Himalaya," and "Cultural Ecosystem Services and Himalaya." Additionally, we incorporated a broad set of terms related to ecosystem services, environmental services, and specific elements in the Himalayan context, ranging from "fuel wood" and "fodder" to "medicinal and aromatic plants."

The comprehensive search was conducted on Google Scholar and Scopus, focusing on literature published between 2000 and 2023 to capture the evolving landscape of ecosystem services research. Global studies were also included for a broader understanding of the concept. More than 200 studies, comprising research articles, review articles, books/book chapters, and reports, were extracted from peer-reviewed and SCOPUS indexed journals. Notably, five influential publications before the year 2000 (Ehrlich and Mooney 1983; Daily 1997; Daily et al. 1997; Costanza et al. 1997; Costanza et al. 1998) were included for a more thorough analysis of ecosystem services principles, approaches, and concepts.

Acknowledging that the review may not encompass all papers mentioning ecosystem services, it nonetheless provides a comprehensive overview of the key literature. This compilation allows for valid conclusions regarding current methodologies, approaches, and trends in ecosystem services research. The study approach is detailed in Fig. 1 and list of parameters for selection of publications are given in Appendix 1. Initially, 342 studies were collected, but 47 duplicates were eliminated. The expansive nature of the ecosystem services concept resulted in studies from adjacent geographic areas due to shared physiographic characteristics and transboundary sites within the region. The study's focus was limited to the physical Himalayan region, with only research from neighboring geographic areas being considered. In the second phase, a thorough examination of 295 articles was conducted, emphasizing studies with clear methodological approaches and substantial contributions to ecosystem services valuation. Opinion papers were excluded, resulting in 256 relevant studies. The final phase involved refining the research to align with the review methodology, prioritizing quantitative and qualitative studies focusing on developing trends, innovative technology utilization (such as Geographic Information Systems and models), landscape-based ecosystem services studies, comparative analyses, and other pertinent factors.

Appendix 1 List of parameters for selection of publication

S. No.	Parameters
1.	Year of Publication
2.	Discipline of 1st author
3.	Publication type (Research article/Book chapter/Report)
4.	Study type (conceptual/case study/review)
5.	Total number of citations

6.	Geographical distribution of study
7.	Data collection methodology
8.	Major category of ecosystem services (PES/RES/SES/CES/IES)
9.	Sub category of ecosystem services(Food and Fuel, Medicinal Plants and TEK, NTFP and Timber, Climate regulation and climate change, Carbon sequestration, Soil nutrient and soil erosion, Water, Cultural landscape and Ecotourism, Religious/Sacred/Spiritual/Social, Mixed)
10.	Driver of change in Ecosystem (Direct/Indirect)
11.	Ecosystem service Valuation Type (Monetary/Non-Monetary)
12.	Ecosystem service valuation Methodology

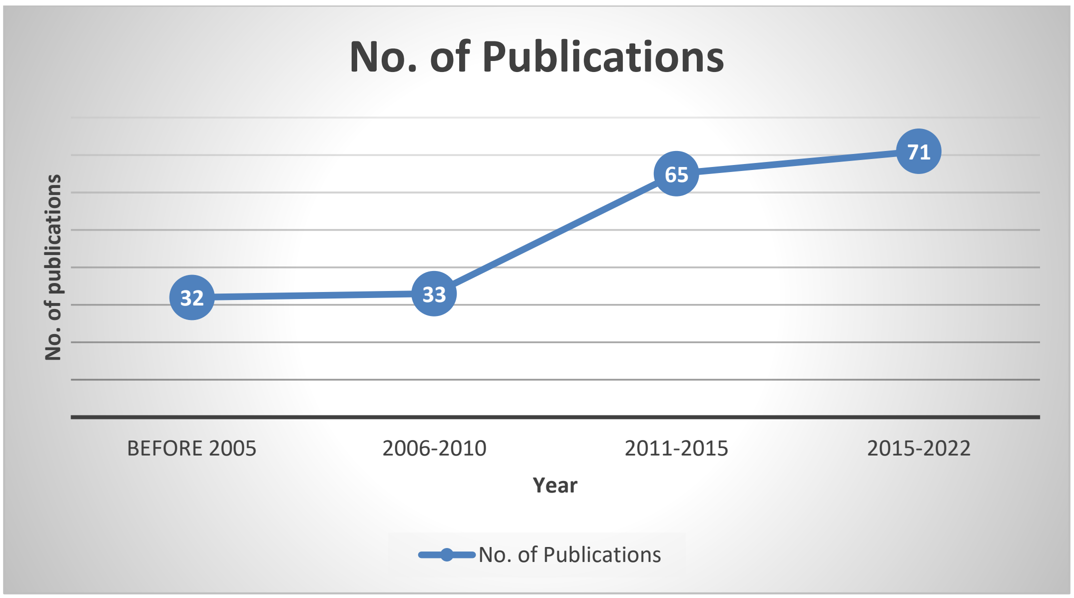

Fig. 1 Number of publications per group of year

The current framework incorporates significant case studies and reports that have conducted extensive study on environmental sustainability in the country. These studies and publications are highly relevant to the process of policy-making. This article includes a selection of review papers that provide a comprehensive examination of major studies conducted worldwide. Based on these criteria, we subsequently refined our investigation to encompass a total of 201 pertinent research papers and other applicable published resources that specifically pertain to the Himalayan region (Table 7). The current framework incorporates significant case studies and reports relevant to environmental sustainability, vital for policy-making. Categorization of the research was structured based on the overarching ES categories outlined by the Millennium Ecosystem Assessment (MEA 2005): Provisioning Services, Regulating Services, Supporting Services, and Cultural Services. This organizational structure enhances the clarity and accessibility of the diverse research findings pertaining to ecosystem services in the Himalayan region.

3 Results

3.1 Overview and general pattern

The review comprehensively explores ecosystem services in the Himalayan region, with a specific focus on the Central Himalaya. A total of 201 publications were analyzed, comprising 182 research articles, eleven book chapters, and eight reports, including notable frameworks like the MEA Framework (2005) and the TEEB Report (2010). Fig. 1 illustrates the distribution of publications over the years, revealing a gradual increase in articles on ecosystem services. Notably, 32 articles were published before 2005, with a subsequent rise to 33 between 2006 and 2010, followed by a steady increase to 65 from 2011 to 2015 and 71 from 2016 to 2023.

The classification of ecosystem services aligns with the MEA Framework (2005), categorizing them into Provisioning Ecosystem Services (PES), Regulating Ecosystem Services (RES), Supporting Ecosystem Services (SES), and Cultural Ecosystem Services (CES) (Fig. 2). To delve deeper into the investigation, these categories were further subdivided (Table 6). According to Table 1, the majority of first authors specialized in ecology and ecosystems (n=53), reinforcing the study's credibility, followed by ecosystem services (n=27) and ecological economics/environmental economics (n=21) (Table 1).

Table 1 Number of publications according to the discipline of the first author

Discipline of 1st author	**No. of publications**
Ecology and Ecosystem	53
Ecosystem services	27
Ecology economics or Environmental economics	21
Ethnobotany; and Medicinal and Aromatic Plants (MAPs)	16
Conservation Biodiversity and Biology	15
Natural Resource Management (NRM)	15
Forest ecology	11
Environment	9
RS, GIS, Ecological modelling	7
Phytochemistry and Plant science	7
Climate change	5
Carbon sequestration, Soil science	4
Landscape ecology	4
Stream, River, Renewable bioenergy, Hydrology and marine ecology	4
Rural livelihood, Sustainable development	3

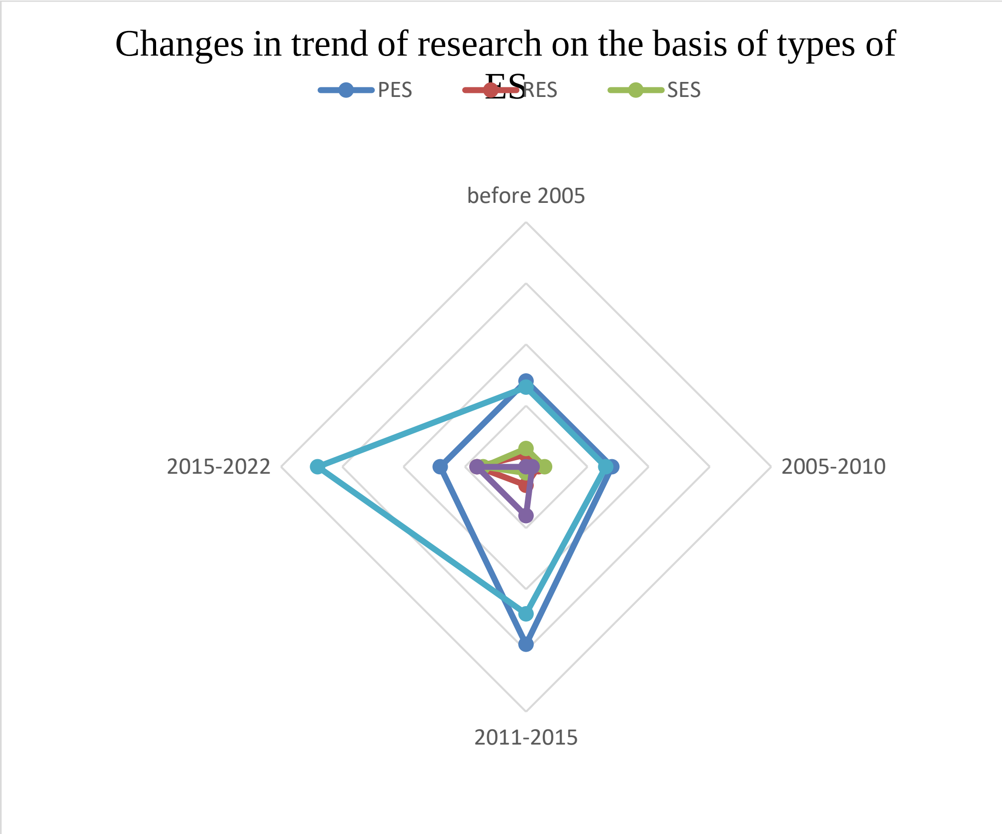

Fig. 2 Changes in trend of research on types of ES

The types of studies were categorized as conceptual studies, case studies, and review studies (Table 6). Surprisingly, nearly 70% of the studies conducted from 2000 to 2022 were case studies (n=141), while conceptual studies (n=42) and review studies (n=18) were relatively fewer. This trend suggests a preference for case studies among scientists, with a declining focus on conceptual and review studies (Table 2; Fig. 3; Fig. 4).

Table 2 Citation groups of included studies

S. No.	**Citation Group (Based on total no. of citation to publication)**	**Total no. of studies included**
1.	1-100	131
2.	101-500	40
3.	Above 500	18
4.	Not available	12

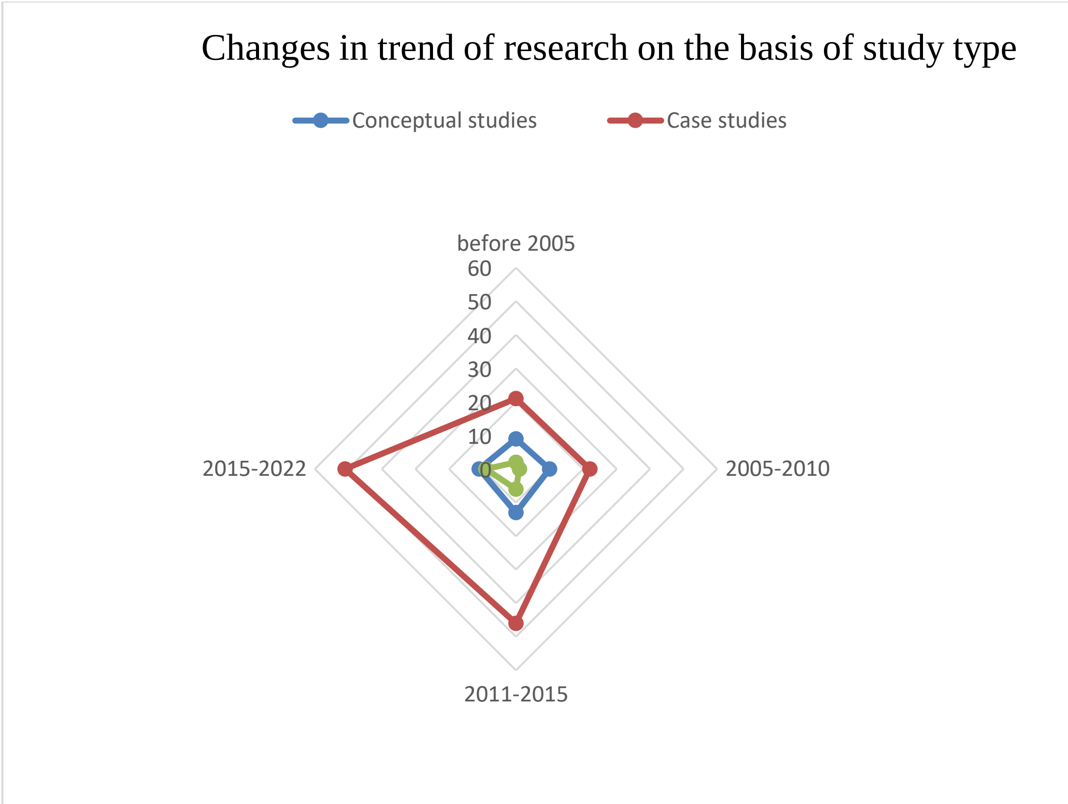

Fig. 3 Changes in trend of research on the basis of study type

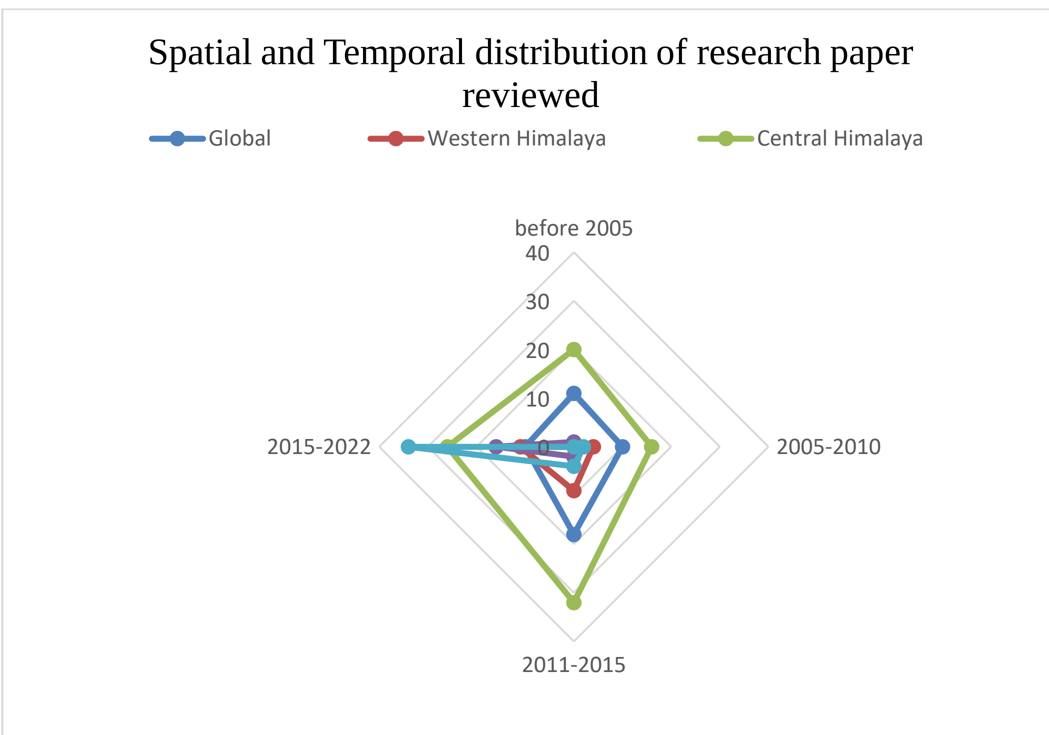

Fig. 4 Spatial and Temporal distribution of research paper reviewed

The methodology employed for data collection was a key focus, with three major groups identified: RS (Remote Sensing) & GIS (Geographic Information System) data, literature, and detailed field surveys. Notably, detailed field surveys (n=132) were the most prevalent, emphasizing the importance of on-site data collection despite its time-consuming nature. Only eight studies utilized RS satellite data, and 61 studies relied on literature. The review underscores the significance of integrated approaches to data collection, emphasizing the effectiveness of combining RS and GIS techniques with field surveys for enhanced accuracy (Table 3).

Table 3 Studies involved data collection and related methods.

S. No.	Major groups of data collection methods	Sub categories of data collection methods	Total no. of studies included (n)
1.	Detailed Field Survey	Field surveys, questionnaires, sampling methods, the PRA/RRA technique	132
2.	Literature methodology	literature	61
3.	RS & GIS data	Remote sensing (RS) and geographic information systems (GIS) (e.g., mapping, RS software analysis, and modelling)	8

The geographical scope of the review encompassed global scenarios, including the Himalaya, categorized into global, western Himalaya, central Himalaya, eastern Himalaya, and other parts of the Himalaya (e.g., Hindu Kush Himalaya). A notable emphasis was placed on the central Himalayan region, with nearly 47% of the research concentrated in this area. In contrast, the Eastern Himalaya and Western Himalaya received less attention, with approximately 20 and 23 studies, respectively (Table 4; Fig. 5). The review ensures a Himalaya-centric perspective while incorporating global studies for conceptual understanding.

Table 4 Geographical distributions of research paper reviewed.

Geographical distribution of study	No. of Publication
Global	51
Western Himalaya	23
Central Himalaya	94
Eastern Himalaya	20
Other Part of Himalaya (HKH, Trans, Greater etc.)	13

3.2 Himalayan ecosystem service evaluation

The majority of research papers were thoroughly examined within the integrated ecosystem services (ES) category, demonstrating the interconnected nature of Himalayan ES. Provisioning ES (PES) emerged as the second-highest category, with approximately 71 research papers analyzed. Supporting ES and cultural ES followed closely with 17 papers each, while the regulating ecosystem services (RES) category had the least number of research publications reviewed, totaling 15 (Table 5). The comprehensive study of Himalayan ES in its entirety was deemed essential due to the intricate interconnections that often make their separate categorization challenging.

Table 5 Research publications reviewed under different category

S. No.	Publications grouped under different category of ES	No. of publication
1.	Integrated ES	84
2.	Provisioning ES	71
3.	Supporting ES	17
4.	Cultural ES	17
5.	Regulating ES	15

Aligning with the Millennium Ecosystem Assessment (MEA) 2005, the five major categories were further divided into ten subgroups (Table 6). Medicinal plants (MP) and traditional ecological knowledge (TEK) were prominent in PES studies (n=32), highlighting their significance in provisioning ecosystem services. Soil nutrients and soil erosion were significant supporting ecosystem services (SES) with 10 studies, while climate regulation (n=10) and carbon sequestration (n=5) stood out as noteworthy regulating ecosystem services (RES). Despite cultural ecosystem services (CES) typically being considered less significant, they played a crucial role in the Himalayan context. Among the 17 CES studies, eight emphasized the value of cultural landscapes and ecotourism, while six focused on social, religious, sacred, and spiritual values. Studies addressing more than one subcategory were grouped under the mixed subcategory, acknowledging the complexity of ES interactions. Notably, water presented challenges during assessment as it could serve both PES and SES functions. For simplicity, water/hydrology was categorized under SES since the research publications predominantly discussed its role as a sustaining or supporting component of ecosystems.

Table 6 Sub-categories of ES of reviewed publication

S. No.	Sub-categories of Studies ES	No. of Publications
1.	Mixed	84
2.	Medicinal Plants and TEK	32
3.	Food and Fuel	26
4.	Climate regulation and climate change	10
5.	Soil nutrient and soil erosion	10
6.	Cultural landscape and Ecotourism	8
7.	Religious/Sacred/Spiritual/Social	6
8.	NTFP and Timber	5
9.	Carbon sequestration	5
10.	Water	4

Considering the drivers of change in ES as a crucial parameter, recent publications were reviewed. Direct drivers, including pollution, invasive species, land cover change, plant nutrients, climate change, and poor management, were highlighted in 59 publications, whereas 50 studies focused on indirect factors such as demographic, economic, social, cultural, and religious influences. Notably, 92 research studies covered both direct and indirect drivers (Table 7).

Table 7 Metrics of cluster analysis

Major metrics of cluster analysis	**Sub-metrics of cluster analysis**	**Total studies included**	**Example**
1. Global (G)	Climate regulation & Climate change (CRCC)	1	Geneletti et al. 2020
	Cultural landscape & Ecotourism (CLE)	5	Tengberg et al. 2012
	Mixed (M)	43	Costanza et al. 1997
	NTFP & Timber (NT)	2	Duncker et al. 2012
2. Western Himalaya (WH)	Carbon sequestration (CS)	1	Goswami et al. 2014
	Climate regulation & Climate change (CRCC)	4	Pandey et al. 2018
	Food & Fuel (FF)	3	Semwal et al. 2014
	Mixed (M)	4	Uniyal et al. 2020
	MP & TEK (MT)	5	Khan et al. 2013
	Soil Nutrient &soil erosion (SNSE)	4	Clift et al. 2010
	Water (W)	2	Momblanch et al. 2020
3. Central Himalaya (CH)	Carbon sequestration (CS)	3	Bhattacharyya et al. 2010
	Climate regulation & Climate change (CRCC)	2	Maikhuri et al. 2001
	Cultural landscape and Ecotourism (CLE)	2	Kala and Maikhuri 2011
	Food & Fuel (FF)	20	Maikhuri et al. 2004
	Mixed (M)	28	Gairola et al. 2009
	MP & TEK (MT)	26	Kala 2005
	NTFP & Timber (NT)	2	Negi et al. 2011
	Religious/Sacred/Spiritual/Social (R/Sa/Sp/So)	5	Sinha and Mishra 2015
	Soil Nutrient &soil erosion (SNSE)	6	Semwal et al., 2003
4. Eastern Himalaya (EH)	Cultural landscape and Ecotourism (CLE)	1	Gurung et al. 2017
	Food & Fuel (FF)	2	Sundriyal and Sundriyal 2003
	Mixed (M)	12	Bhatta et al. 2016
	MP & TEK (MT)	1	Das et al. 2012
	NTFP & Timber (NT)	1	Uprety et al. 2016
	Religious/Sacred/Spiritual/Social (R/Sa/Sp/So)	1	Dorji et al. 2019
	Water (W)	2	Chowdhury and Behera 2020
5. Other part of the Himalaya (OH)	Carbon sequestration (CS)	1	Tolangay and Moktan 2020
	Climate regulation & Climate change (CRCC)	3	Xu et al. 2009
	Food & Fuel (FF)	1	Chandrasekhar et al. 2007
	Mixed (M)	8	Sandhu and Sandhu 2015

The review also delved into ecosystem services valuation, with a total of 54 studies analyzing the value, including both monetary (n=28) and non-monetary (n=3) assessments. Various valuation methods were employed, such as market pricing methods (n=23), contingent value methods (CVM) or willingness to pay (WTP) (n=5), carbon credit methods (n=1), and mixed methods (n=25). The use of mixed methods involved employing more than one valuation type, contributing to diverse valuation techniques. However, 23 research investigations applied both monetary and non-monetary valuation methods. In contrast, the remaining 147 studies did not consider ecosystem valuation.

4 Discussion

4.1 Provisioning Ecosystem Services (PES)

Ecosystem services refer to the tangible benefits or resources obtained from ecosystems, which can be immediately consumed or traded on various markets (MEA 2005). These services include sustenance and textiles, combustible timber, animal feed, foraged edible resources, non-timber forest products (NTFP), and freshwater resources (MEA 2005; TEEB 2011). Maikhuri et al. (2004) conducted a study in the central Himalayan region focusing on the economic potential of plant species like Aegle marmelos, Berberis aristata, Hippophae rhamnoides, Myrica nagi, Rubus ellipticus, and Prunus armeniaca. They proposed creating value-added consumable items such as jam, jelly, juice, and squash from wild fruits to generate revenue for impoverished rural communities. Similarly, Negi et al. (2011) identified and prioritized wild edible plants in the region, aiming to enhance community awareness and explore the economic potential, distribution, ethnobiology, and optimal harvesting time.

Sundriyal and Sundriyal (2003) investigated six fruit species widely used by local communities in the Himalayas, noting low concentrations within forest stands and an unpredictable fruit-collection technique, posing a threat to species survival. Non-timber forest products (NTFPs) play a crucial role in food security and income generation for socioeconomically disadvantaged populations. Uprety et al. (2016) analyzed NTFP utilization patterns, identifying unsustainable harvesting practices and insufficient marketing efforts as obstacles. They suggested sustainable harvesting methods, local-level value addition, and marketing strategies to promote NTFP utilization in the Kanchenjunga landscape. Semwal et al. (2014) documented edible or commercially valuable mushroom species in Uttarakhand and Himachal Pradesh, highlighting the selective gathering of Cordyceps sinensis and Morchella species. Khan et al. (2013) found a substantial abundance of medicinal plant species in the Naran valley, while Kala (2005) recorded 243 herbal medicine formulations used by traditional Vaidyas in Uttarakhand.

The agrobiodiversity of Central Himalayan agroecosystems has changed due to socio-cultural, economic, and environmental transformations (Maikhuri et al. 2001). Dhyani (2018) measured leaf debris collected for forest-dependent agriculture in the Western Himalayas, enhancing farmers' earnings through cattle husbandry. Wood is a primary energy source in rural India, with many depending on fuel wood and biomass sources. Kumar and Sharma (2009) examined fuel wood consumption fluctuations in the Himalayan region based on altitude, while Hussain et al. (2017) studied the effects of fuel wood extraction by the Van Gujjar population on Uttarakhand's forests. Khan et al. (2019) explored the relationship between ecosystem water yielding capacity and water supply benefits at regional and sub-regional levels. Joshi and Negi (2011) found oak forests offering provisioning services valued at 5676 (73.22 USD) per individual annually, primarily in fodder and fuel wood, while pine forests provided services valued at 4640 (59.85 USD) per person per year. Naudiyal and Schmerbeck (2018) examined the correlation between provisional ecosystem services and five distinct vegetation types in the Central Himalayan region.

4.2 Regulating Ecosystem Services (RES)

The regulation of ecosystem processes provides various advantages, including the maintenance of air quality, climate regulation, water regulation, erosion control, water purification, waste treatment, regulation of human diseases, biological control, pollination, and storm protection (MEA 2005). To address the challenges posed by climate change, it is crucial for regional and local-scale research to collectively comprehend the phenomenon. Pandey et al. (2018) conducted a study assessing the utilization of climate-related information among communities in the Himalayan foothills of rural India. The focus was on identifying obstacles hindering the effective implementation of adaptation planning and activities in these areas. Xu et al. (2009) reported a rapid decline in the volume of Himalayan glaciers due to climate change, raising concerns about water supplies and agricultural output.

Greenhouse gas concentrations, particularly carbon dioxide (CO2), are increasing due to unrestricted human activity (Bruhwiler et al., 2021). Vegetation and soil play a crucial role in capturing and sequestering carbon in terrestrial ecosystems (Singh et al., 2015). According to the State of Forest Report by the Forest Survey of India (FSI) in 2021, India's forested areas store 7,204 million metric tons of carbon, with soil organic carbon accounting for 56.18%. Understanding mechanisms influencing soil organic carbon (SOC) fluctuations is vital for sustaining soil productivity and mitigating global warming effects (Bhattacharyya et al. 2010). Goswami et al. (2014) assessed the potential of agroforestry land use systems in carbon sequestration in the central Himalayan region. Their study suggested that long-term soybean-wheat rotation in sandy loam soil resulted in carbon and nitrogen sequestration. The size fraction ranging from 0.25 to 0.1 mm was identified as a suitable indicator for long-term carbon and nitrogen sequestration.

Research indicates that deforestation increases the likelihood of flooding due to reduced water retention and organic content in the soil (Chomitz 2007). Joshi and Joshi (2019) studied the role of Himalayan forests in water purification and ecosystem services provision. Tripathi (2015) highlighted the economic impact of floods, with a 2% reduction in GDP and 71,426 recorded fatalities from 2005 to 2015. Vegetation's significance in flood regulation lies in reducing water velocity and enhancing percolation in floodplains and watersheds (Crossman et al. 2019).

4.3 Cultural Ecosystem Services (CES)

Cultural ecosystem services are the intangible benefits that humans obtain from ecosystems, particularly in cultural and social dimensions. These advantages encompass spiritual enrichment, cognitive development, introspection, leisure activities, and aesthetic experiences. The range of benefits includes cultural diversity, spiritual and religious values, traditional and formal knowledge systems, educational values, inspiration, aesthetic values, social connections, a sense of belonging, cultural heritage values, and recreation and ecotourism (MEA 2005). In the Indian context, cultural ecosystem studies predominantly focus on examining recreational value, ecotourism, and traditional livelihoods linked to trees. The COVID-19 pandemic has significantly impacted this focus due to the requirement to stay at home, intensifying existing psychological concerns. Simultaneously, it has underscored the stress-alleviating advantages offered by natural environments (Basu et al. 2021). Gurung et al. (2017) emphasize that enhancing the preservation of ecosystem functions and services contributes to both social and ecological resilience.

Residents in the Himalayan region, according to Das et al. (2012), possess substantial knowledge of herbal remedies. However, the risk of diminishing traditional plant applications looms as exposure to modernization increases over time. Trivedi et al. (2018) present empirical data supporting the significance of sacred groves in facilitating cultural and environmental services and preserving biodiversity. Sinha and Mishra (2015) conducted a thorough examination of the Hariyali sacred landscape (HSL) in the Garhwal Himalayas, revealing the potential for increased awareness of economic, ecological, and cultural importance. The authors suggest interventions involving neighboring villages in temple rights and rituals, along with a transparent approach to fund management, to enhance community engagement and financial contribution (WTP) for landscape preservation. The traditional knowledge of Himalayan people holds immense significance in sustainable living, medicinal applications, cultural legacy preservation, biodiversity conservation, and climate change adaptability. Kala's (2005) study in Uttarakhand, India, on the contemporary utilization of medicinal plants by traditional Vaidyas showed 45% classified as wild species and 55% as cultivated species, with 20% growing in fields and 80% in kitchen gardens. Pandey et al. (2018) stress the importance of incorporating traditional knowledge in addressing climate change and restoring ecosystem services.

The concept of ecotourism, encompassing sustainability factors like social, environmental, cultural, and economic aspects (UNEP, 2002), has gained prominence in India. Chaudhary et al. (2022) highlight the economic and societal advantages of ecotourism, as supported by various scholarly investigations (Goodwin and Chaudhury 2017). Das and Hussain (2016) found a positive perception towards ecotourism among local residents in villages surrounding Kaziranga National Park.

4.4 Supporting Ecosystem Services (SES)

Ecosystem services play a pivotal role in supporting various facets of the environment and human well-being. These services are crucial for generating other ecosystem services and are distinct from provisioning, regulating, and cultural services due to their indirect or long-lasting impacts on human populations. This is in contrast to the relatively rapid and short-term repercussions associated with alterations in provisioning, regulating, and cultural services. Soil formation and retention, nitrogen cycling, and water cycling are acknowledged as critical ecosystem services (MEA 2005). Clift et al. (2010) conducted a study attributing the formation of the Indus Delta to silt erosion originating from the western Himalaya. Fluctuations in monsoon intensity have impacted the delta, with erosion shifting towards southern regions correlating significantly with areas experiencing intense summer monsoon precipitation. The study suggests that robust erosion, as hypothesized by existing tectonic models of the Greater Himalaya, relies on a strong summer monsoon. The sustained intensification of the monsoon, attributed to the uplift of the Tibetan Plateau, is proposed to play a vital role in governing the tectonic evolution of the Himalayas through monsoon-driven erosion processes.

Semwal et al. (2003) found that the rainy season is associated with the highest rates of nitrogen (N) and phosphorus (P) release. In tree-crop mixed agroforestry, the leaf litter of these species, if considered the sole nutrient source for crops, indicates less nutritional stress for rainy season crops compared to winter season crops. Gairola et al. (2009) explored the correlation between forest disturbance impacts on litterfall and nutrient return in subalpine forest ecosystems in the Indian west Himalaya region. Distinct subalpine forests exhibited variations in litter component nutrient concentrations, with sensitivity observed across different forest types and nutrient compositions. The study by Nayak et al. (2019) examined ecosystem services in rice fields in the Eastern Himalaya region. It revealed that the economic value of soil formation was ₹0.20 $\times 10^{-5}$ per hectare per year, while nitrogen fixation was valued at ₹402.50 (5.053 USD) per hectare per year. Nitrogen cycling ecosystem services in agri-ecosystems have garnered significant attention from the scholarly community (Sharma & Rana 2014).

Momblanch et al. (2020) emphasized the utility of freshwater resource system models for understanding interconnected systems and formulating effective catchment management strategies. The effectiveness of these models is contingent upon the spatial distribution of climate change and infrastructure management's influence on river flows. Their study also highlighted a correlation between family education, ownership of tube wells, private containers, and household awareness of ecosystem service regulation and promotion. Chowdhury and Behera (2020) conducted a study in West Bengal, India, analyzing factors contributing to awareness disparities among households near traditional water bodies. They found a positive correlation between education level, ownership of tube wells, private tanks, and household awareness regarding the regulation and maintenance of ecosystem services.

4.5 ES Management challenges

The Himalayan ecosystem confronts significant challenges in environmental management, primarily stemming from inadequate forest management practices. These practices have led to adverse consequences such as deforestation, soil erosion, biodiversity loss, and diminished water resources. The challenges are attributed to the expansion of agriculture and settlements, unrestricted exploitation of timber and other forest resources, and excessive grazing. Climate change further poses a threat to the region's biodiversity and natural resources. Anticipating the enduring consequences of diverse ecosystem management methodologies is crucial for effective development and execution of sustainable strategies.

Chandra et al. (2021) highlight limited knowledge about alpine vegetation responses to contemporary changes in the Himalaya, including resource utilization, climate change, and increased developmental and tourism activities. Gurung et al. (2021) identify barriers hindering effective climate change adaptation and ecosystem services management, such as climate hazards unpredictability, limited technological access, prevailing belief in fate, inadequate government policies, restricted resources, and insufficient weather information. Ineffective governance and monitoring impede ecosystem service operational efficiency, as noted by Uniyal et al. (2020).

Kala and Maikhuri (2011) delve into conflicts between local communities and reserve authorities, centered on the prohibition of traditional bio-resource collection rights and restrictions on anthropogenic activities within core zones. Insufficient monitoring and governance contribute to the inefficiency of payment for ecosystem services, as indicated by Uniyal et al. (2020). Bhatta et al. (2016) argue for a participatory management strategy. To align local stakeholder objectives with national forestry objectives, public collaborations and comprehensive decision-making are essential (Dorji et al. 2019). The goal is to safeguard human welfare by upholding ecosystem service functioning, enhance community and ecosystem adaptability to environmental changes, and monitor changes in biodiversity and ecosystem services. Collaboration among authorities is vital for sustainable ecosystem management, supporting livelihood benefits, and aligning with global conservation agendas (Gurung et al. 2017). Sandhu and Sandhu (2015) stress the need for local and global initiatives integrating poverty alleviation and biodiversity conservation in the Himalayas. Institutional partnerships, proposed by Tiwari and Joshi (2015), aim to enhance knowledge and resource accessibility from international to national levels.

Sharma et al. (2022) advocate for utilizing satellite and field-based monitoring techniques, impact evaluation methods, and risk modeling in glacial lake management. Pandey et al. (2018) emphasize incorporating adaptation strategies within a framework combining top-down and bottom-up approaches for sustainable development. Geneletti and Dawa (2009) examine tourism impacts on trekking in the Himalayan region, emphasizing environmental consequences such as urban development encroachment and proliferation of tourist structures. Sahani's (2021) study introduces a hybrid SWOT-AHP-Fuzzy AHP model for prioritizing ecotourism strategies in the Western Himalaya region. Urban expansion and tourism development must be closely monitored to establish suitable spatial planning regulations (Geneletti and Dawa 2009). Enhancing institutional systems through voluntary stakeholder engagement is imperative. For effective payment for ecosystem services (PES), non-monetary incentives like capacity-building initiatives, livelihood training, and skill development for rural areas are advisable. Prioritizing stakeholder integration, valuing ecosystem services, and capacity-building for primary and secondary stakeholders are essential for the efficacy of the ecosystem services model (Uniyal et al. 2020).

5 Future Prospects and Research Gaps

The Himalayan region, renowned for its unparalleled biodiversity and critical ecosystem services, stands at the forefront of global conservation concerns. As we delve into the future prospects and research gaps, it becomes imperative to address emerging technologies for conservation, delineate research priorities in Himalayan ecology, and find a delicate balance between development imperatives and conservation goals.

5.1 Emerging Technologies for Conservation

The application of cutting-edge technologies is increasingly becoming indispensable in the field of conservation. Remote sensing technologies, such as satellite imagery and unmanned aerial vehicles (UAVs), play a pivotal role in monitoring land-use changes and assessing the health of ecosystems in the Himalayas (Fonji and Taff 2014). Integrating artificial intelligence and machine learning algorithms into these technologies enhances our ability to analyze vast datasets efficiently, enabling more precise and timely conservation interventions (Xu et al. 2021). Furthermore, the use of DNA barcoding and metabarcoding techniques has revolutionized species identification, providing crucial insights into the Himalayan biodiversity (Reva et al. 2015). These technologies collectively offer a robust framework for conservation practitioners and policymakers to make informed decisions in the face of complex ecological challenges.

5.2 Research Priorities in Himalayan Ecology

To address the myriad challenges faced by Himalayan ecosystems, it is crucial to outline specific research priorities. Long-term ecological monitoring initiatives are paramount, providing baseline data for understanding the impacts of climate change and human activities on biodiversity (Pandey et al. 2018). Additionally, studying the interactions between species and their habitats, especially in the context of changing climatic conditions, is vital for predicting and mitigating potential ecological disruptions (Kaur et al. 2022; Das & Mishra 2023). Research focused on the resilience of Himalayan ecosystems to disturbances and the identification of keystone species will contribute substantially to conservation strategies tailored to this unique region.

5.3 Balancing Development and Conservation Goals

The Himalayan region is not only a biodiversity hotspot but also a crucial resource for the communities residing in its vicinity. Balancing development aspirations with conservation imperatives requires a nuanced approach. Implementing sustainable development practices, incorporating community-based conservation models, and engaging in multi-stakeholder collaborations are essential steps (Dutta and Dutta 2023). Striking a balance between infrastructure development and ecological integrity necessitates the integration of conservation into policy frameworks, ensuring that economic growth aligns with environmental sustainability (Jiayu et al. 2024). Emphasizing the importance of preserving traditional knowledge systems and involving local communities in decision-making processes will foster a holistic and inclusive approach to development in the Himalayan region.

6 Conclusion

In conclusion, the Himalayan ecosystem is undergoing significant changes due to climate change and human activities, leading to glacier melt, water insecurity, and shifts in vegetation patterns. These alterations have profound effects on ecosystem services, impacting millions of lives and agricultural productivity in the region. Addressing the depletion of these services requires a comprehensive approach, incorporating climate regulation, carbon stocks, soil nutrients, and cultural aspects.

Efforts should focus on sustainable management practices, including the regulation of timber harvesting, promotion of sustainable agriculture, and monitoring of grazing activities. Climate change adaptation strategies, such as reforestation and soil conservation, are crucial for long-term ecosystem viability. Involving local communities in decision-making processes, promoting community-based forest management, and considering their perspectives in policy decisions are essential steps. Additionally, fostering international collaboration, supporting research and monitoring, and promoting ecotourism can contribute to sustainable forest management and address global environmental challenges. Overall, a balanced approach that integrates socio-cultural perspectives is necessary to restore equilibrium between economic interests and ecological imperatives in the Himalayan region.

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On behalf of all authors, the corresponding author states that there is no conflict of interest.

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