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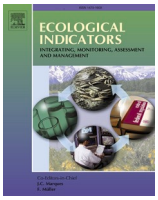

Review

Changing discourses in the third pole: A systematic review of climate change impact on biodiversity in the Hindu Kush Himalaya

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ABSTRACT

Climate change has emerged as one of the major threats to biodiversity and the Hindu Kush Himalaya (HKH) is facing the challenges due to a higher rate of elevation dependent warming and erratic rainfall. The rich biodiversity and bounty of ecosystem services provided by this 'water tower' and the 'Third Pole' are under higher risk. Though there is scattered and sectoral knowledge available, comprehensive understanding on climate change and its impact on biodiversity is lacking in the HKH. To fill this gap, a systematic literature review using search, appraisal, synthesis, and analysis (SALSA) was undertaken to look at temporal and spatial trends of research focusing on the impacts of climate change on biodiversity and ecosystem services. The increasing trend and evolution of research from sectoral to multidisciplinarity approach with increasing focus on impacts suggested a strong influence from regional priority and global discourse. There is a clear pattern of biophysical and environmental focused research in the early phase of the 1990s to societal concerns highlighting vulnerability, adaptation, and mitigation measures at the later phases. The review also revealed an increasing trend in multidisciplinary, networking and bringing innovative tools in research linking climate change and biodiversity. However, the research showed greater focus in the Tibetan plateau and alpine ecosystem with decreasing interest in the forest ecosystems, and a very negligible focus on wetlands. Studies on impact assessments are increasing but at a relatively low rate. Better representation of investments based on vulnerable ecosystems, underrepresented countries and collaborative regional research on emerging priority areas such as restoration and larger scale nature-based solutions could contribute to climate resilience in the HKH.

1. Introduction

Climate change has recently emerged as one of the five major global threats to biodiversity with a million species at risk of extinction (IPBES, 2019). Frequent reporting of the hottest years in recent times (Tollefson, 2016; Vossen, 2021) and biodiversity loss (IPBES, 2019) are intricately linked, reinforcing each other, and challenging the very existence of humanity (Pörtner et al., 2021). The recent IPCC report (see IPCC, 2021) is now "unequivocal" and presents "established fact" that human activities are causing the warming and 1.5 °C—a target set by the 2015 Paris climate agreement, will very likely be reached within the next 20 years (Nunez et al., 2019). Mountain ecosystems, the essential components of life support systems, are facing the brunt of climate change as warned by scientists (Knight, 2022). This indicates a double-edged sword for humanity as biodiversity loss increasingly threatens ecosystems and human well-being (Pecl et al., 2017).

The Convention of Biological Diversity (CBD) defines "biodiversity loss" as "the long-term or permanent qualitative or quantitative reduction in components of biodiversity and their potential to provide goods and services, to be measured at global, regional and national levels" (CBD COP, VII/30). This definition has been realized and recognized as a major contemporary global challenge, which is also mentioned in the recent World Economic Forum's Global Risk Report (WEF, 2022). Though intergovernmental environmental initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and CBD already exist, the global attention to Intergovernmental Panel on Climate Change (IPCC) was increasingly higher in terms of investment and global priority compared to biodiversity (Legagneux et al., 2018). An effort has now been made to change this trend and highlight the equal importance of biodiversity for sustainable development, climate change mitigation and adaptation, and contribution to human well-being (WEF, 2022).

There is an increasing number of literatures looking at the impacts of climate change on biodiversity (Rana et al., 2021), ecosystems (Cetin

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et al., 2023; Schirpke et al., 2023), species (Varol et al., 2022), human settlements (Cetin et al., 2020) and conservation planning at landscape level (Adiguzel et al., 2020). Climate change impacts assessments on phenology (Menzel et al., 2020), vegetation shift, species movements are also emerging (Tekin et al., 2022). Though there is a strong realization on interdependence of climate change and biodiversity and need for synergy (Perga et al., 2023), there are limited efforts made in analysing the trends through comprehensive review looking at how climate change impacts biodiversity and ecosystem services (Gupta and Singh, 2023).

The Hindu Kush Himalaya (HKH), the highest and the most fragile mountain ecosystems in the world, is arguably one of the most biodiverse regions on Earth (Mittermeier et al., 2011) and is vulnerable to climate change (Krishnan et al., 2019). More than 40 % of the HKH region's geographic area is covered by protected area networks, due to its high and fragile ecosystems that host rich biodiversity (Chaudhary et al., 2022). Advocated as the 'Third Pole' and 'Water Tower of Asia' due to the largest mass of glaciers outside the two poles and the region with four out of 36 Global Biodiversity Hotspots, the HKH region is in the limelight for both climate change and biodiversity (Xu et al., 2019). It is evident that, due to elevation dependent warming, the HKH is witnessing a higher rise in temperature compared to the other mountain ranges and higher than the global average (Krishnan et al., 2019). Warming has cascading consequences on biodiversity, water, people's livelihood, and food security among others (Xu et al., 2009; 2019).

Once identified as a data deficit region, there is increasing interest in climate change science, ecosystem services and biodiversity in the HKH (Wester et al., 2019). A recent study found the HKH to be the most researched mountain region in the world (Gurgiser et al., 2022) and another report warns that the 1.5 °C target set by the 2015 Paris climate accord is too hot for the HKH as by that rate, the region is likely to warm by 2.1 °C (Krishnan et al., 2019). Climate change is already posing risks to biodiversity in the HKH (Chettri et al., 2010). The signs of impacts are reported from species to ecosystems (Kumar, 2012; Shrestha et al., 2012; Anderson et al., 2020; Penjor et al., 2021; Wangchuk et al., 2021). However, the disciplinary and geographical focus is largely skewed to climate sciences and biophysical studies within small and confined geographical areas. Climate studies are also confined to temperature changes, glacier retreat, water dynamics, and hazards (Bhutiyani et al., 2008), whereas biophysical studies focused on biodiversity are largely on vegetation or tree line shift (Manish et al., 2016; Sigdel et al., 2018), species (Dar et al., 2021; Pant et al., 2020), community studies (Yadav et al., 2021; Gillette et al., 2022); phenology (Hart et al., 2014; Mohandas et al., 2015; Mishra and Mainali, 2017); people's perceptions (Chaudhary et al., 2011; Wangchuk and Wangdi, 2018) among others. There have been limited efforts and investments into understanding the impact of climate change on fragile ecosystems and biodiversity at the scale of the HKH. The integrative approaches that focus on climate change impacts on biodiversity and ecosystem are still limited in the HKH (Kumar and Chopra, 2009; Chettri et al., 2010; Forrest et al., 2012; Shrestha and Bawa, 2014; Dahal et al., 2021).

Considering the urgency reflected in the recent 6th IPCC Report by Working Group II on tackling climate change (IPCC, 2022), nature-based solutions could be a promising option as the concept provides an opportunity to have a better understanding of the nexus between climate change, biodiversity, and ecosystem services in the HKH. In this review, we explored the nexus between climate change and its impact on biodiversity and ecosystem services to understand the state of knowledge, existing priorities, and emerging opportunities considering contemporary discourses including nature-based solutions. We posed the following three research questions to understand the past work and bring forward gaps and opportunities: -

i) What are the thematic, temporal, and spatial research trends on the impact of climate change on biodiversity and ecosystem services in the HKH?
ii) How the research priorities changed to address the evolving contemporary challenges and which institutions were involved?
iii) What is the state of knowledge and where are the gaps?

2. Methods

We performed a systematic literature review, covering the geographical area of the HKH (Fig. 1). We used a research framework suggested by Grant and Booth, (2009), which has been increasingly applied in different disciplines in the HKH (Kandel et al., 2021; Sharma et al., 2021; Shrestha et al., 2022; Adhikari et al., 2022). It is a framework of locating, appraising, and synthesizing the concept of search, appraisal, synthesis, and analysis (SALSA). Though the framework has been used in some disciplines, it has not been applied to climate-related biodiversity studies to date in the HKH. We believe the applied method (see Fig. 2) offers considerable promise in the review field, but it will need periodic updating to inform and support policy and practice and adjust to evolving research needs.

2.1. Search

While exploring the search options, we considered various possibilities for collating literature. However, we narrowed it down to Scopus (Elsevier) and Web of Science (WoS) considering the comprehensive options available for indexed journals and being widely used (Mongeon and Paul-Hus, 2016), while Google Scholar and the Google search engine were also used to cross triangulate any promising and important literature which were not indexed in Scopus or Web of Science.

We searched for articles within Scopus and Web of Science database using the keywords (in all fields): [Himalaya*‖ or -Hindu Kush Himalaya*‖ or -Tibetan plateau*‖ or -name of the regional member countries such as Afghanistan, Bangladesh, Bhutan, China, India, Nepal, Pakistan, Myanmar*‖] AND [-climate change*‖ or -global warming‖] AND [Biodiversity] AND [Ecosystem Services]. A wide range of criteria for inclusion of a maximum number of literatures was ensured by using names of sub-regions and provinces found within the HKH, different subsections of biodiversity (birds, amphibians, mammals, flora, butterfly, flora etc.) covering diverse ecosystems (mountains, rangeland, grassland, forest, freshwater, agroforestry, agriculture) including keywords such as people's perception, temperature, precipitation, extreme weather among others. We limited articles published only in English, and up to 2021.

2.2. Appraisal

We collated a total of 767 literatures published over 28 years (1993–2021). Our review resulted in 676 literatures from the Scopus and 531 from the Web of Science with a total combined number resulting in 1207. However, after removing the duplicates and grey literature (conference papers, workshop proceedings etc.), we considered 767 literatures for further analysis (S1). We retained these final 767 literatures based on the syntax used either in the authors keywords or in the abstract. We also cross-checked with the data collected from google-scholar, added if there is any key literature missing and then organized the dataset in the given excel sheet format, which was extracted and used for further analysis.

2.3. Synthesis

The step is a qualitative approach to synthesise the derived knowledge by exploring, interpreting, and extracting narratives from the acquired data (Vicente-Saez and Martinez-Fuentes, 2018). Hence, the first step was to homogenise the data extracted from Scopus and Web of Science and create a database of consistent information. As a follow up, we ensured the date of publication, authors keywords, focused thematic areas including dominant ecosystems, institutional information were

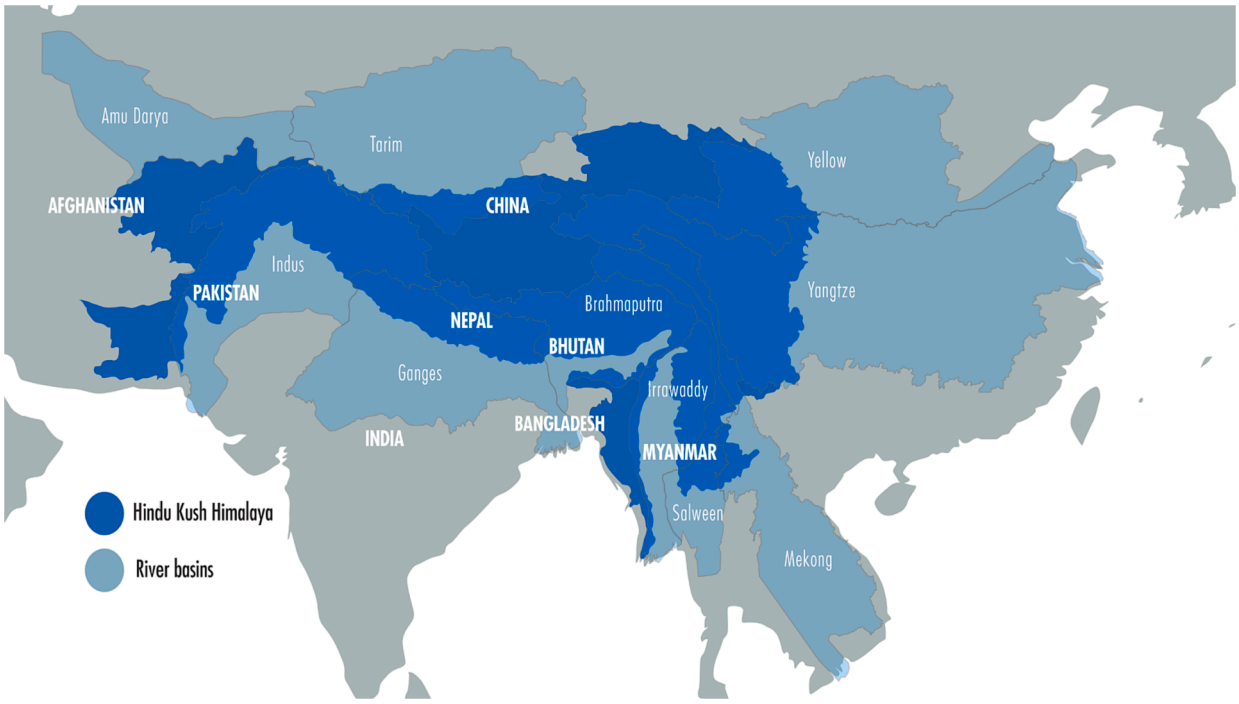

Fig. 1. The Hindu Kush Himalaya (dark blue) and the river basins (light blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

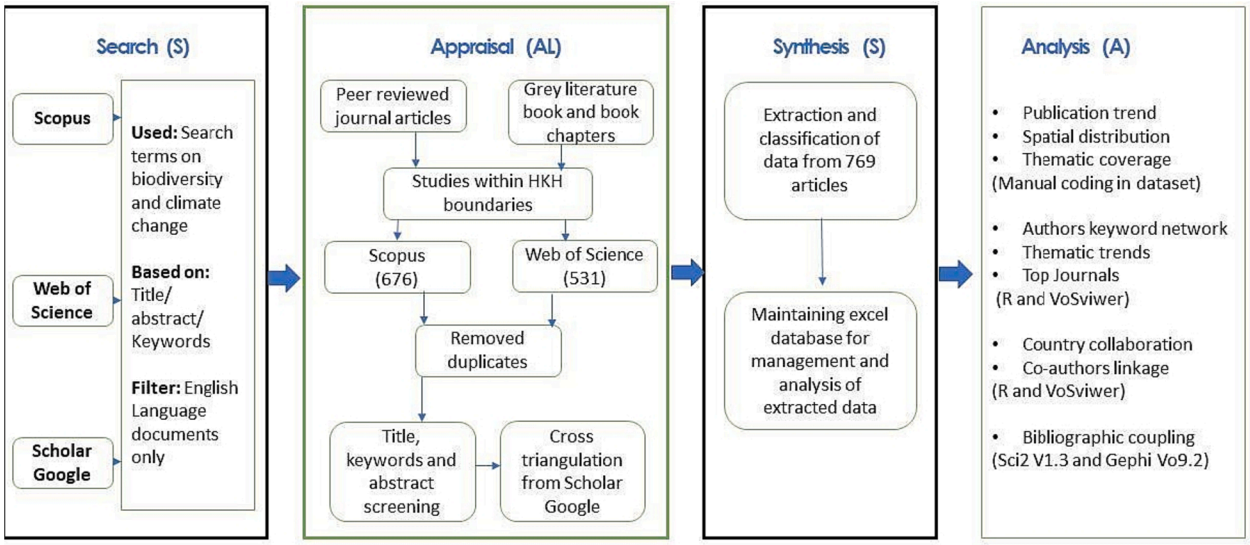

Fig. 2. Schematic flow of the methodology used for the review.

complete and met the requirement of the three research questions set above. A separate dataset was prepared by coding study area/country, year of publication, thematic areas and ecosystems based on Prescott et al. (2000). These datasets were then maintained and managed in MS Excel for analysis.

2.4. Analysis

Analysis involved evaluating the synthesised data to gain meaningful information and addressing the research questions from the HKH. We quantified and analysed the categories to explain the results. We used three sets of analytical approaches to address the research questions (Fig. 2). We identified the spatial (high elevation alpine ecosystem, low elevation forests, wetlands and agro-ecosystem), temporal, and thematic research trends on the impact of climate change on biodiversity and ecosystem services by manually coding relevant information and categorizing it in respective thematic categories following Prescott et al. (2000). To understand the evolution of past research and contemporary challenges, we used a combination of the "bibliometrix" package (Aria and Cuccurullo, 2017) of R v4.1.2 (R Core Team, 2022) as well as VOSviewer v1.6.17 (van Eck and Waltman, 2010) to analyse the authors' keywords and the evolution of thematic coverage over the period. Similarly, R and VOSviewer were used to analyse organisational engagement and collaboration networks respectively; and Sci2 v1.3 (Sci2 Team, 2018) to conduct bibliographic coupling and Gephi v0.9.2 (Bastian et al., 2009) to visualize the results following Boyack and

Klavans, (2010) as indicated in Fig. 2.

3. Results

3.1. Thematic, temporal, and spatial study trends

Our analysis resulted in four dominant ecosystems and eight thematic priority areas as shown in Fig. 3. The highest number of studies were reported from high elevation alpine ecosystems (28 %) followed by forest ecosystems (24 %), agro-ecosystems (19 %), and wetland ecosystems (14 %). The remaining 15 % did not mention the studied ecosystem explicitly (Fig. 3). Considering the thematic areas, the most dominant thematic topic covered in all the four ecosystems was mountain biodiversity (Fig. 3). Agrobiodiversity and forest biodiversity were dominant in agro-ecosystem and forest ecosystems whereas wetland ecosystems covered diverse thematic coverage. Studies on species and taxonomy, agrobiodiversity, and dryland biodiversity were the least among the published literature and impact assessment mostly covered alpine and forest ecosystems (Fig. 3).

Further analysis on temporal evolution of research priorities considering the three time periods on ecosystems and thematic focus revealed interesting trends (Fig. 4). Though the number of publications increased in most ecosystems, the proportion of publications that focused on forest and wetland ecosystems decreased. This was because there was an increase in the proportion of publications focused on agro-ecosystems. The proportion of publications that focused on the alpine ecosystem was consistent throughout the three time periods (Fig. 4a). Likewise, similar trends were also observed for mountain biodiversity (ecosystems, species, flora, fauna) with increasing trends on agro-biodiversity, species, and sustainable tourism (4b). However, there were variations such as decreasing priorities on forest, dryland, and aquatic biodiversity (Fig. 4b). Within the assessment of impacts, there was an increasing trend in agriculture, consistent focus on alpine grasslands, and decreasing priority on forests (Fig. 4b).

Our review revealed that 1993 was the year when climate change impacts in the HKH was first reported (Fig. 5). We observed three distinct periods where research on climate change and biodiversity

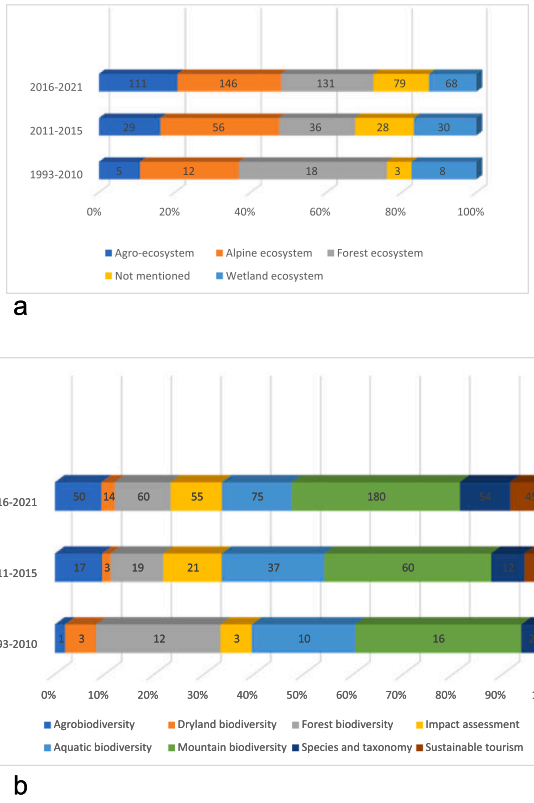

Fig. 4. Changing paradigm on (a) ecosystems (b) and thematic focus of the literature in the HKH.

progressed. During the period between 1993 and 2010, publications were comparatively low, with a maximum of five publications in 2005, and most years having one or no relevant publications. However, from 2005 onwards, there was a gradual increase in number of publications, with an average of eight articles per year, and with a maximum of 11

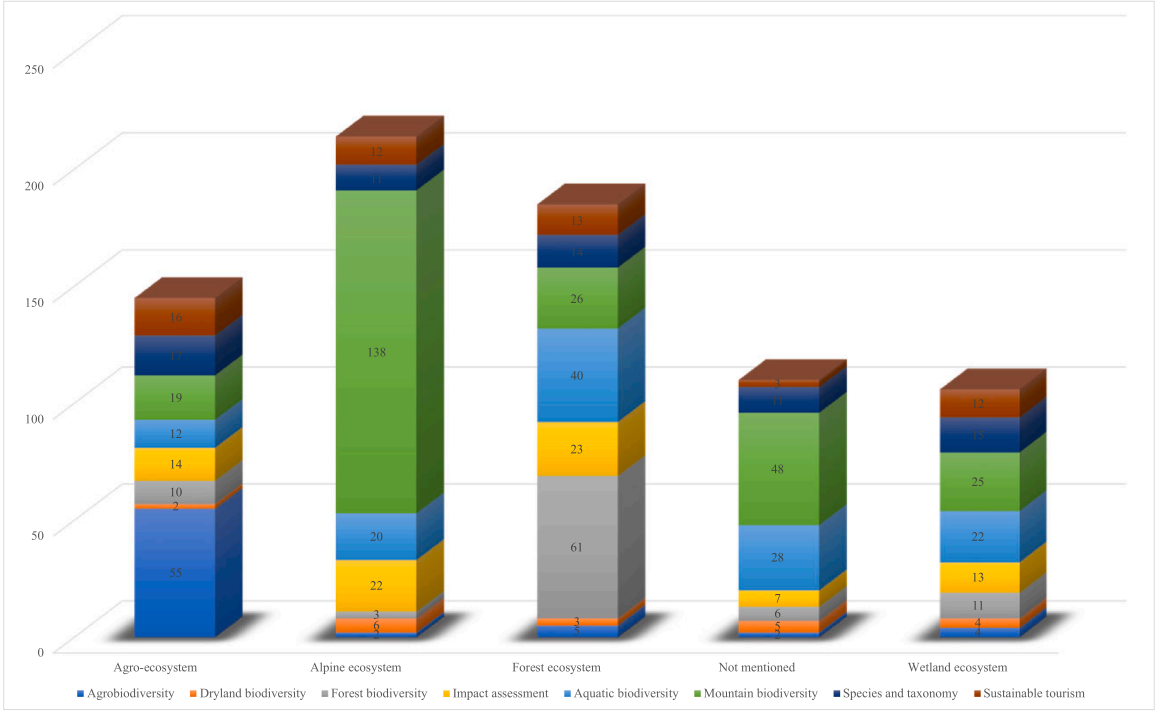

Fig. 3. Number of the literature showing thematic research in each ecosystems from the HKH.

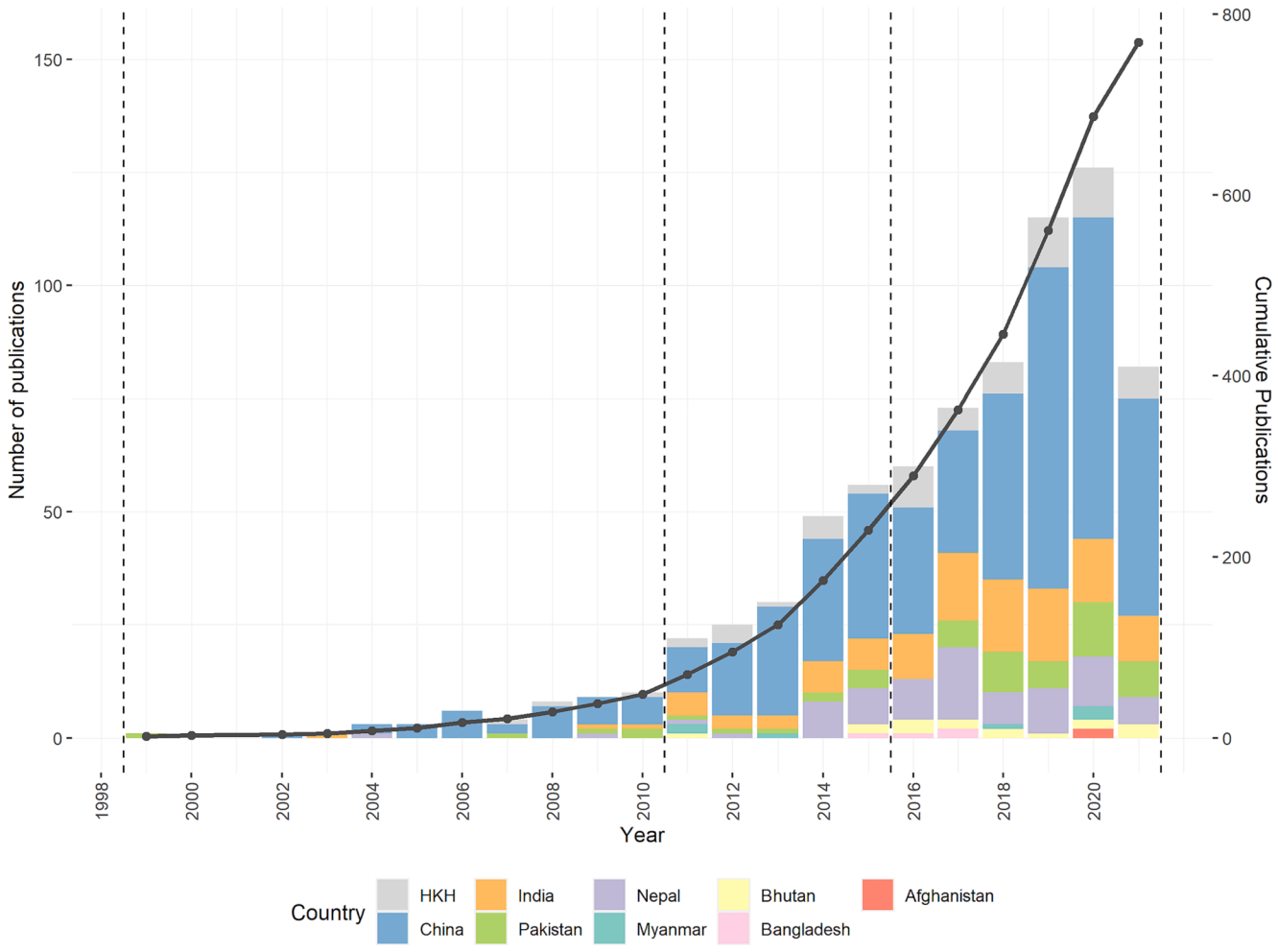

Fig. 5. Temporal trends of selected research articles and cumulative numbers published in each member country of the Hindu Kush Himalaya.

relevant articles being published in 2009 during this period Between 2010 and 2015, the growth in publications was progressive, with the maximum number of publications being 54 in 2015 (Fig. 5). And from 2016 to 2021, the trend continued to increase with the highest record of 125 in 2020.

The spatial coverage of literature indicated that China has the highest number of publications with over 56 % of the total followed by India (14 %), Nepal (10 %) and the least was from Myanmar with only two publications (Fig. 5). Notably, only 9 % of the literature dealt at a regional scale, beyond national boundaries covering either entire or part of the HKH.

3.2. *Changing research priorities*

The 28 years of recorded literature showed changing dynamics in research priority as reflected in keywords used (see S2 for top 50 keywords extracted from VoSviewer). The initial research period (1993 to 2010) highlighted conventional research priority with sectoral topics such as climate change, ecosystem degradation, forest ecology and productivity, use of tools and technologies. While "climate change" was used in combination with other cluster keywords such as "climate warming", "global warming", "global change", "warming" etc., ecosystem degradation was reflected by "degradation" and "human impacts". Analyzing the keywords, alpine ecosystems were the primary focus and represented by keywords such as "alpine ecosystem", "rangeland", "alpine", "grazing", "pastoralism" etc. Forest ecosystem studies with focus on "forest" and "conifer forest" ecosystems were also reported. This period also saw use of technology such as remote sensing and tree ring studies but very few studies on impacts and vulnerability (S1). From 2011 to 2015, the keywords highlighted "climate change" but with addition of "adaptation" and "vulnerability" reflected by other keywords such as "adaptive capacity", "threats", "risk" along with impacts on "phenology", and "alpine wetlands". This phase also introduced novel tools such as "modis", "species distribution models" and a new subject on "diatoms". As the research progressed (2016–2021), there was further diversification in literature, with emerging topics such as "agriculture", "food security", "drought" and "ecosystem services" became emerging topics along with "resilience", " and "perception". Interestingly, more diversified keyword combinations and tools such as "tree-ring", "dendrochronology", and "maxent" were also observed. This period also brought the link to "glaciers" and "permafrost". Alpine grasslands and forests were the primary ecosystems focused as priority ecosystems. A clear understanding of the evolving use of keywords can be found in S1 where percentage of use of keywords such as "climate change" "biodiversity", "vulnerability", "adaptation" was found in an increasing number and new areas of research keywords can be observed. It should be noted that the use of "climate change" increased in frequency over the entire period and "vulnerability" and "adaptation" increased significantly during 2011 to 2015 and 2016–2021 respectively (see S1).

Our bibliographic coupling network (Fig. 6) further supported the research priority on thematic clusters. As the network distinctly showed four major clusters, examining each cluster closely based on keywords with higher number of citations and associated keywords represented by

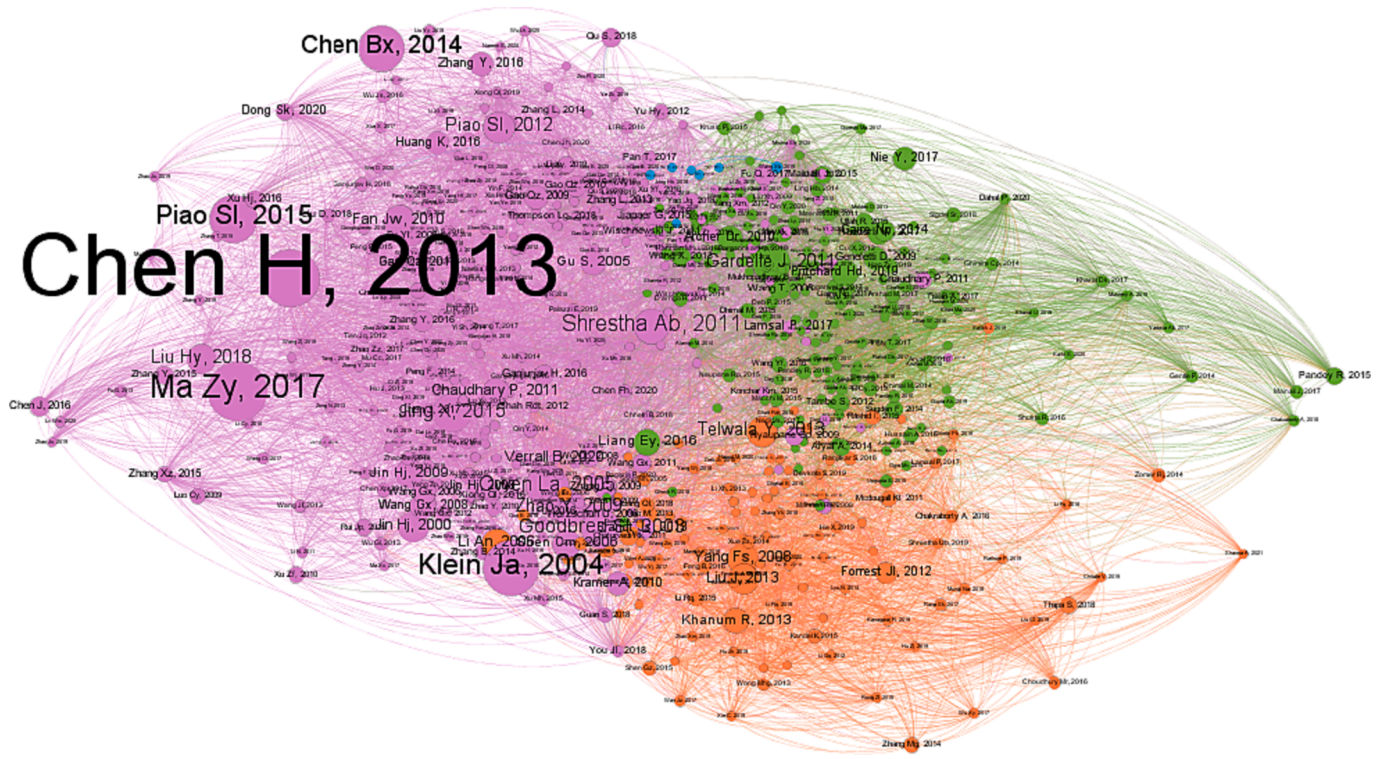

Fig. 6. Network Visualization of Bibliographic Coupling of studies researching climate change in the Hindu Kush Himalaya. Each node indicates a research article labeled by the first author and its publication year. The size of the nodes is proportional to the number of global citations of the paper.

size of nodes and linkage, we found that the changing priorities are clearly reflected. For example, the biggest cluster (purple) consisted of research mainly focusing on ecosystem responses to climate change such as seed dispersal, soil moisture, nitrogen and carbon content, and net primary productivity. Most research in this cluster consisted of control experiments (e.g. experimental warming), biophysical modeling, and quantitative research and site-specific, almost exclusively focused on the Qinghai Tibetan plateau with a very few exceptions from the Hindu Kush Himalaya. The second cluster (orange) had studies focused on biodiversity and ecosystem linking with climate change impacts such as impacts on species and phenology etc. as also seen in S1. The geographic scale of most studies in this cluster was either national or regional, and the spatial coverage was also comparatively wider than the previous cluster, which included studies in all the HKH countries except Afghanistan. Biophysical modeling and quantitative research were also seen as a major focus of studies in this cluster. The third cluster (green) was more focused on human-nature interactions and the effects of climate change on human wellbeing representing majority of research from recent periods. Broadly, climate change risk, vulnerability, adaptation, and mitigation were the four major themes within this cluster. The studies within this cluster also explored measuring the risks of climate-induced disasters, understanding the vulnerability to drought and water shortages, climate change adaptation measures, agriculture and food security, and household perceptions to climate change. Studies in this cluster usually employed a mixture of biophysical modeling and sociocultural evaluation to understand human-nature interactions. The geographic coverage of this research was extremely wide covering the HKH except Afghanistan while the scale of the research also varied from site-specific to national. The last cluster (blue) was only a handful and consisted of research exclusively on water with use of keywords such as permafrost, precipitation, drought etc. In terms of global citation, we can see in the figure that the first cluster (purple) was generally more cited than others, showing the prominence of research on ecosystem degradation and climate change impact at the ecosystem level with majority of research on alpine and forests ecosystems.

The source dynamics (Fig. 7) show that publication in Science of the Total Environment is relatively new but has been increasing exponentially. Meanwhile, Agricultural and Forest Meteorology, PLOS One and Journal of Mountain Science published relevant articles relatively earlier. The point to be noted here is that all these journals are emerging as multidisciplinary platform documenting diverse disciplines and in an integrated manner. We also found that journals published on climate change sciences in the HKH before 2002 (e.g. Climate Research, International Journal of Environment and Pollution) are no longer relevant at present for the research topic as reflected by top 20 journals (see S3). This indicates that changing priority contributed to multidisciplinarity increased in the recent year corresponding to a widening scope on the subject from climate change to impacts, vulnerability, adaptation, and mitigation (Fig. 7).

3.3. *Networking and collaborative research*

Climate change and its impacts on biodiversity and ecosystem services are emerging subjects of research in the HKH. The collated data indicated that there were 56 countries engaged in research and 53 countries collaborated for joint research as indicated by the connecting lines in Fig. 8. Most of the research comes from the University of the Chinese Academy of Sciences, with about 40 % more research than any other institute. This is indicated by the size of the corresponding-colored circle and linkages followed by the United States (purple color overlapping with Nepal), India, and Nepal. Countries such as Mongolia, Ireland, and Mexico also collaborated for research in the HKH (Fig. 8). While countries such as China, the United States, and European countries collaborated strongly with other countries, collaboration among the HKH member countries was limited apart from between Nepal and India.

4. Discussions

Biodiversity supports human well-being in many ways, either

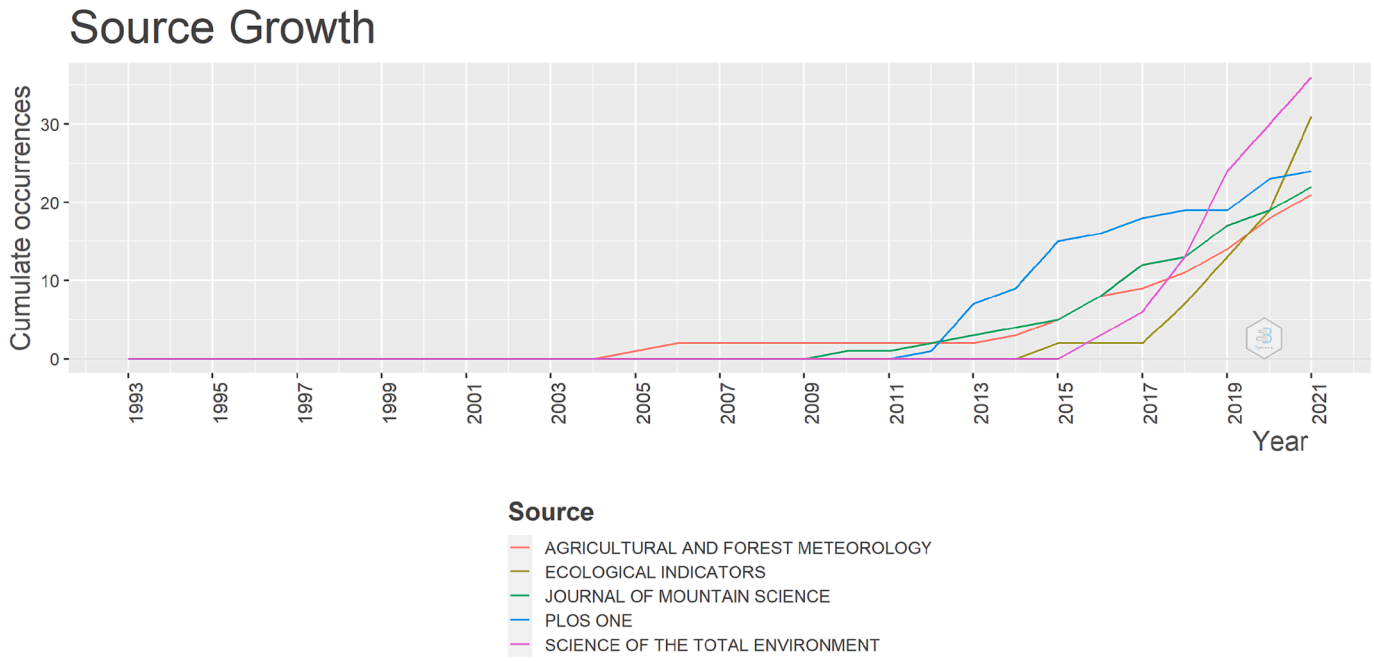

Fig. 7. Growth of top five journals that published research on Climate Change and biodiversity in the Hindu Kush Himalaya.

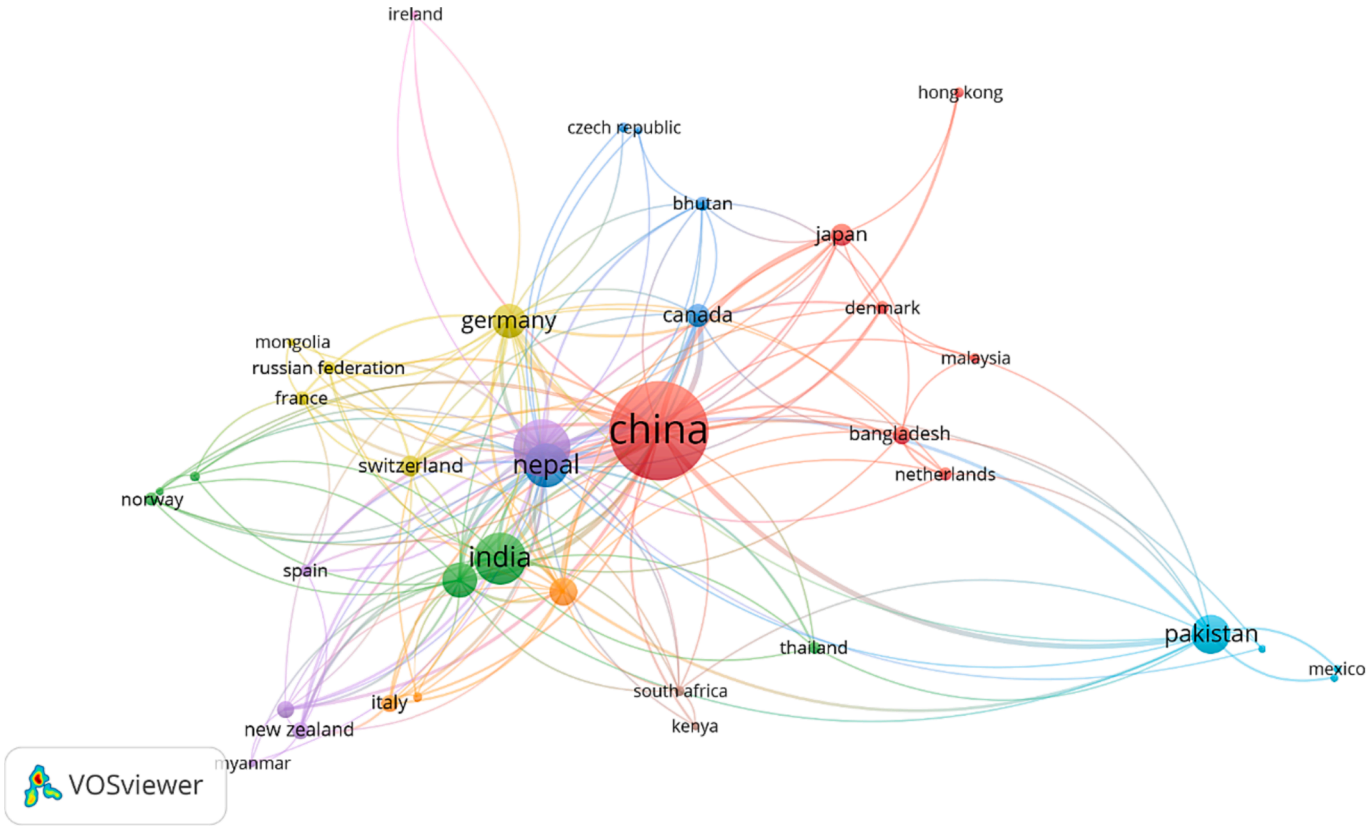

Fig. 8. Co-authorship collaboration country networks on climate change and biodiversity research on the Hindu Kush Himalaya. Nodes and colors represent the country affiliation of the research institute, and size of the nodes represent the number of occurrences of the country in the number of literatures. Links and their sizes represent the collaboration and frequency of collaboration between two connecting countries.

directly through enhanced ecosystem functions and services or indirectly by increasing the resilience of such functions to global change. Climate change is considered as one of the five greatest threats to biodiversity (IPBES, 2019) and is the most important threat for the mountain ecosystems (Schmeller et al., 2022). However, these two disciplines, though strongly interdependent, were largely taken as separate pathways in research and policy advocacy (Hisano et al., 2018). In recent years, efforts have been made to synergise these two critically

important disciplines (Arneth et al., 2020; Shin et al., 2022). There is an increasing recognition that, although the climate change and biodiversity crises are fundamentally connected, they have been primarily addressed independently and a more integrated global approach is essential to tackle these two global challenges (Pettorelli et al., 2021; Gupta and Singh, 2023). However, little effort was made to understand these two disciplines together at national (Vittoz et al., 2013), regional (Sintayehu, 2018), mountain ecosystems (Palomo, 2017; Gurgiser et al., 2022; Knight, 2022) or global levels (Bellard et al., 2012; Nerini et al., 2019; Payne et al., 2020). Here we bring our narratives based on the results from this review work.

4.1. Thematic, temporal, and spatial study trends

The Hindu Kush Himalaya is known for its highest mountain ecosystem with rich biodiversity (Sharma et al., 2010; Xu et al., 2019). Our thematic analysis highlighted that the focus of past research was largely on mountain biodiversity followed by aquatic biodiversity, forest biodiversity, with an increasing trend on climate change impact research as also observed in other mountains such as the Andes (Llambí et al., 2019), and the Alps (Parisod, 2022). This is a positive sign of widening the scope of research based on prevailing risk from climate change and its consequences to biodiversity and human wellbeing (Basnet et al., 2019; Wester et al., 2019; Rana et al., 2021; Chang et al., 2022). As freshwater ecosystems are critical for aquatic biodiversity (Allen, 2010), a fair proportion of interest was revealed in this thematic area followed by forest – an important ecosystem where a large proportion of people and the wildlife are dependent on diverse ecosystem services and habitat (Joshi and Joshi, 2019; Chettri et al., 2021). Species and taxonomy are of special significance in the HKH due to the presence of charismatic species such as snow leopard (*Panthera uncia*), tiger (*Panthera tigris*), Asian elephant (*Elephas maximus*), greater one-horned rhinoceros (*Rhinoceros unicornis*) and an increasing number of new species being discovered (Allen, 2010; Xu et al., 2019). Similarly, thematic topics such as agrobiodiversity is manifested by rich cultural and ethnic diversity along with associated traditional knowledge (Chaudhary and Bawa, 2011; Negi et al., 2021; Schneiderbauer et al., 2021). It was documented that linguistic and cultural diversity is strongly linked to biodiversity and this is evident in the HKH (Gorenflo et al., 2012; Hua et al., 2019). However, climate change impact assessment, especially disaster induced biodiversity and ecosystem services loss though critically important for the region like the HKH, is limited but increasing as also suggested by Rana et al. (2022).

Our results of increasing temporal trends in research on climate change and biodiversity are consistent with global trends (Legagneux et al., 2018) as well as other mountain ecosystems (Palomo, 2017; Knight, 2022). The publications pattern was in line with other reviews on biodiversity (Rana et al., 2021), ecosystem services (Gangahagedara et al., 2021; Kandel et al., 2021; Wang et al., 2021; Liu et al., 2022) and other science disciplines (Rana et al., 2022; Chang et al., 2022). However, the growth trend was skewed to countries like China, India, and Nepal due to increasing higher proportion of geographical coverage in the HKH (Sharma et al., 2021) and increasing investment and interests in the Tibetan Plateau (Chang et al., 2022) and the Himalayas (Pepin et al., 2022; Rana et al., 2022). Less priority was observed in countries like Bhutan, Bangladesh, Myanmar, and Afghanistan and this could be largely due to less priority for research investment and political unrest (Kandel et al., 2021; Sharma et al., 2021).

It may be noted that the key global documentation on biodiversity and climate change started with flagship publications such as the Millennium Ecosystem Assessment report published in 2005 (MA, 2005) and the Economics of Ecosystems and Biodiversity (TEEB, 2010). The AR4 report published in 2007 (IPCC, 2007) brought global attention towards the Hindu Kush Himalaya due to the alarming signals on climate change. Similarly, the formal establishment of IPBES in 2012 gave a fresh impetus to debates over the role of the social dimension and Sustainable Development Goals (SDGs) in nature conservation through Nature's Contribution to People framework (Díaz et al., 2018; Martin-Lopez et al., 2019; Adhikari et al., 2022). The recent IPCC reports also highlight the consequences of climate change on nature and its implications for reaching SDGs (IPCC, 2022; IPCC, 2021) which could have accelerated the research on ecosystem services as also suggested by Chaudhary et al., (2015). Therefore, it indicates that the research trends are strongly influenced by global discourses (Nerini et al., 2019; Payne et al., 2020; and regional trends (Kandel et al., 2021; Karki et al., 2021) and the availability and investment of funds as suggested also by Legagneux et al., (2018).

4.2. Changing research priorities

The keyword analysis suggested diversification of research priorities from the conventional focus on climate studies, biodiversity, anthropogenic pressures, and ecosystem degradation domains to contemporary concerns on climate change, ecosystem services, risks, vulnerability, livelihood, and adaptation strategies supporting recent trends (Mondal and Zhang, 2018; Dorji et al., 2019). The changing scenarios and focus on water, food productivity and food security, linking with disaster along with other drivers of change such as land use change indicated how social-ecological system thinking evolved over the period (Bhattacharjee et al., 2017). This clearly indicates the increasing trend of inclusion of social sciences in biodiversity conservation and climate change mitigation measures (Uprety et al., 2017; Negi et al., 2021). Interestingly, there was an increasing trend of using modern tools linking climate change science with biodiversity and human wellbeing (Manish et al., 2016; Thapa et al., 2018; Boral and Moktan, 2021).

The bibliographic coupling network highlighted four focused areas indicating nexus between climate change with biodiversity, ecosystems and human wellbeing emphasizing on climate change impacts as also reported by Gupta and Singh, (2023). Increasing trends in modeling and quantitative research and human-nature interactions focusing on climate change risk, vulnerability, adaptation, and mitigation show the widening scope from conventional research on thematic topics to multidisciplinarity (Pauna et al., 2018).

Corresponding with the multidisciplinary requirement to look at climatic change science and biodiversity and ecosystem services, the five most used journals correspond to multidisciplinary science journals such as Science of the Total Environment, Ecological Indicators, PLOS ONE among others corresponding to what was also seen in Kandel et al., (2021). In the present review, multidisciplinary journals were dominant, and more interestingly, multidisciplinary research is increasing over time. This is a good indication of holistic understanding and synergy building between thematic disciplines as also seen in other mountain areas (Payne et al., 2020).

4.3. Networking and collaborative research

The network analysis indicates the dominance of China in research with a higher number of publications and large number of institutions engaged in research. It also has wider collaboration with 24 out of 56 countries as well as strong network with the United States. Similar results were reported with a higher number of case studies beside the United States at global (Chaudhary et al., 2015; Gangahagedara et al., 2021) and regional scales for ecosystem services (Kandel et al., 2021) and other disciplinary sciences (Chang et al., 2022; Rana et al., 2022). However, other bigger players played the dominant role while considering global scale – largely by the west (see Pauna et al., 2018). It is to be noted that since large-scale research is being performed in the Tibetan Plateau and the Himalaya, the dominance of China, India and Nepal seems reasonable (Verrall and Pickering, 2020; Chang et al., 2022; Rana et al., 2022). However, there is very limited collaboration seen among the member countries of the HKH though the ecosystem is shared as common heritage and the impact of climate change on biodiversity and

biodiversity loss are common issues.

5. Conclusion

Climate change is emerging as a major driver of environmental change in the Hindu Kush Himalaya – a cornucopia of biodiversity and water tower of Asia – the source for diverse ecosystem services. This 'Third Pole' has witnessed noticeable attention in climate change science due to elevation-dependent warming and melting of glaciers. Our systematic literature review from 1993 to 2021 highlighted four broad regional trends. First, there is an increasing interest in climate change and biodiversity following other mountain and global trends, largely influenced by global discourses. Second, there is a clear indication of diversification in research priority from conventional and sectoral research to multidisciplinary approach focusing on social-ecological interaction with environmental considerations. This is evident from the changing scenarios on priorities from species conservation and ecosystem-based research to climate change and impact perspectives focusing on vulnerability, food security and adaptation. However, in doing so, certain disciplines, geographical areas and ecosystems are being less prioritised for research. Third, there is an increasing interest from more than 50 countries to collaborate for research in the HKH. This collaboration is bringing new innovations, technologies, and more importantly financial investment for research in the region. However, there was disparity in thematic focus, regional collaboration and country or geographical priorities. And fourth, there are promising pathways followed by researchers addressing contemporary issues such as climate change, impacts, adaptive measures, and recommendations for inclusion of social sciences, technologies, and adaptive measures among others.

Our review also identified knowledge, information and research gaps that need special attention. Our understanding on climate change science, biodiversity and their interlinkages are limited to a few and concentrated geographic areas such as Tibetan plateaus, Indian Himalayas, and Nepal. We must ask questions on how the complex ecosystems of the HKH are witnessing climate change and how they affect ecosystems, species, and genetic diversity. And how can countries like Afghanistan, Bhutan, Bangladesh and Myanmar could receive investment for capacity development, research and conservation interventions including restoration.

Likewise, a decreasing trend in research on critical ecosystems such as dryland, forests, and wetland ecosystems, and very negligible attention to the agro-systems is worrisome as most mountain people depend on these ecosystems for their subsistence livelihoods. Future research must look at the state of these ecosystems and answer how these ecosystems and their interfaces are facing the impact of climate change and how they are impinging the anticipated progress on global goals such as Paris Agreement, Sustainable Development Goals, Kunming-Montreal Global Biodiversity Framework etc.

In addition, scattered and sporadic research, less attention to subjects such as climate induced disaster and its consequences and limited emphasis on scale and interconnected ecosystems do provide a common ground for countries to come together and develop common strategies. With increasing incidents of disaster, and developmental activities adaptation and resilience building through restoration could be explored. However, while working for the corrective measures, the future research must explore and look at the question such as – what are the impacts of climate and water induced disasters to people and biodiversity in transboundary landscapes and river basins and what are their economic costs?

Considering the transcending nature of ecosystem from one country to other and interdependency due to upstream and downstream linkages, movement of large migratory species and ever-increasing threats from various drivers of change including climate change, it is high time for the regional member countries of the HKH develop a common vision for safeguarding the fragile ecosystem of the HKH. Therefore, a stronger inter-countries collaboration, collective efforts on global negotiation for representative investment and collective efforts for innovation on restoration and resilience building interventions are inevitable for safeguarding the fragile ecosystem of the HKH. To address this, we must ask how and what type of institutional mechanism would be instrumental to foster collaborative research among the member countries of the Hindu Kush Himalaya and how to strengthen regional cooperation for collective actions.

6. Disclaimer

The views and interpretations contained in this publication are those of the authors. They do not imply the expression of any opinion by ICIMOD concerning the legal status of any country, territory, city, or area under its authorities, concerning the delimitation of its frontiers or boundaries, or the endorsement of any product.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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