Journal of Asia-Pacific Biodiversity 9 (2016) 1–10

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Journal of Asia-Pacific Biodiversity

journal homepage: http://www.elsevier.com/locate/japb

Journal of Asia-Pacific Biodiversity

Review article

Biodiversity research trends and gap analysis from a transboundary landscape, Eastern Himalayas

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
16 November 2015
Accepted 17 November 2015
Available online 1 December 2015

Keywords:
Kangchenjunga landscape
knowledge gaps
regional cooperation
research trends

ABSTRACT

The Kangchenjunga landscape, a transboundary complex shared by Bhutan, India, and Nepal, is one of the biologically richest regions in the Eastern Himalayas. Owing to the remarkable biodiversity, the three countries came together to enhance regional cooperation in conservation and development in 2012. To start a strategic conservation intervention, the status of our knowledge base on biodiversity of the landscape is the most important stepping stone. In this paper, we traced the history of biodiversity research in the Kangchenjunga landscape, and present the research trends over time and subject interests. Meanwhile, we also identified key research and knowledge gaps and future priorities. For this, we analyzed 500 peer-reviewed journal articles (until 2014) relating to biodiversity, which were retrieved from the web platform 'Google Scholar' and other peer-reviewed journals. The review showed that the landscape received attention from the scientific community as early as the 1840s, and grew progressively after the 1980s. Research on fauna (especially mammals) and flora (especially angiosperms) is most notable, but with major gaps in systematic research of their ecology, whereas invertebrates other than butterflies appear to be neglected. There is a need for systematic research with long-term monitoring that would allow us to understand changes occurring within the landscape.

Introduction

Mount Kangchenjunga, the third highest mountain of the world, has been identified as one of the most important transboundary landscapes in the Eastern Himalayas (CEPF 2005; Chettri et al 2008; Rastogi et al 1997). The complex, shared by Nepal in the east, India (Sikkim, North Bengal, including Darjeeling) and Bhutan in the west, is one of the biologically richest landscapes in the Eastern Himalayas (WWF and ICIMOD 2001; Yonzon 2000). Located in the Himalayas, one of the 34 Global Biodiversity Hotspots (Mittermeier et al 2004), the southern slope of the Kangchenjunga Landscape (KL), with an area of 25,080.8 km^2 and situated between latitudes of 26°21′40.49″ to 28°7′51.25″ North and longitudes of 87°30′30.67″ to 90°24′31.18″ East, has been identified as one of the six transboundary landscapes in the Eastern Himalayas (Chettri et al 2009; ICIMOD et al 2015). The diversity of habitat types found in the landscape ranges from the Himalayan Alpine Meadows to the Eastern Himalayan Broadleaf and Conifer Forests, and to the Terai-Duar Savannas and Grasslands, all of which are among the Global 200 Ecoregions (Wikramanayake et al 2002). On the basis of altitudinal range, the habitat types found in the KL can be broadly categorized into: (1) tropical; (2) subtropical; (3) warm temperate; (4) cool temperate; (5) subalpine; and (6) alpine types. These extreme topographic variations of the landscape provide diversity in the microclimatic conditions and the habitat types, enriching the landscape as a biodiversity repository (Chettri et al 2008).

The complex includes 19 protected areas (PAs), nine of which are transboundary in nature (ICIMOD et al 2015; Figure 1). The designated PAs cover an area of 7176.4 km^2 that accounts for 30% of the total landscape area. The KL provides habitat to about 160 mammal species, 580 bird species, and 600 butterfly species, and some of these are globally threatened (Chaudhary et al 2015a; ICIMOD et al 2015). Some of the flagship species that reside in the landscape include the snow leopard (*Panthera uncia*), musk deer (*Moschus chrysogaster*), Himalayan black bear (*Ursus thibetanus*), and Tibetan antelope (*Pantholops hodgsonii*) in the high mountains, the red panda (*Ailurus fulgens*), takin (*Budorcas taxicolor*) and clouded leopard (*Neofelis nebulosa*) in the mid hills, and the Royal Bengal tiger (*Panthera tigris*) and Asiatic elephant (*Elephas*

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Peer review under responsibility of National Science Museum of Korea (NSMK) and Korea National Arboretum (KNA).

http://dx.doi.org/10.1016/j.japb.2015.11.002
pISSN2287-884X eISSN2287-9544/

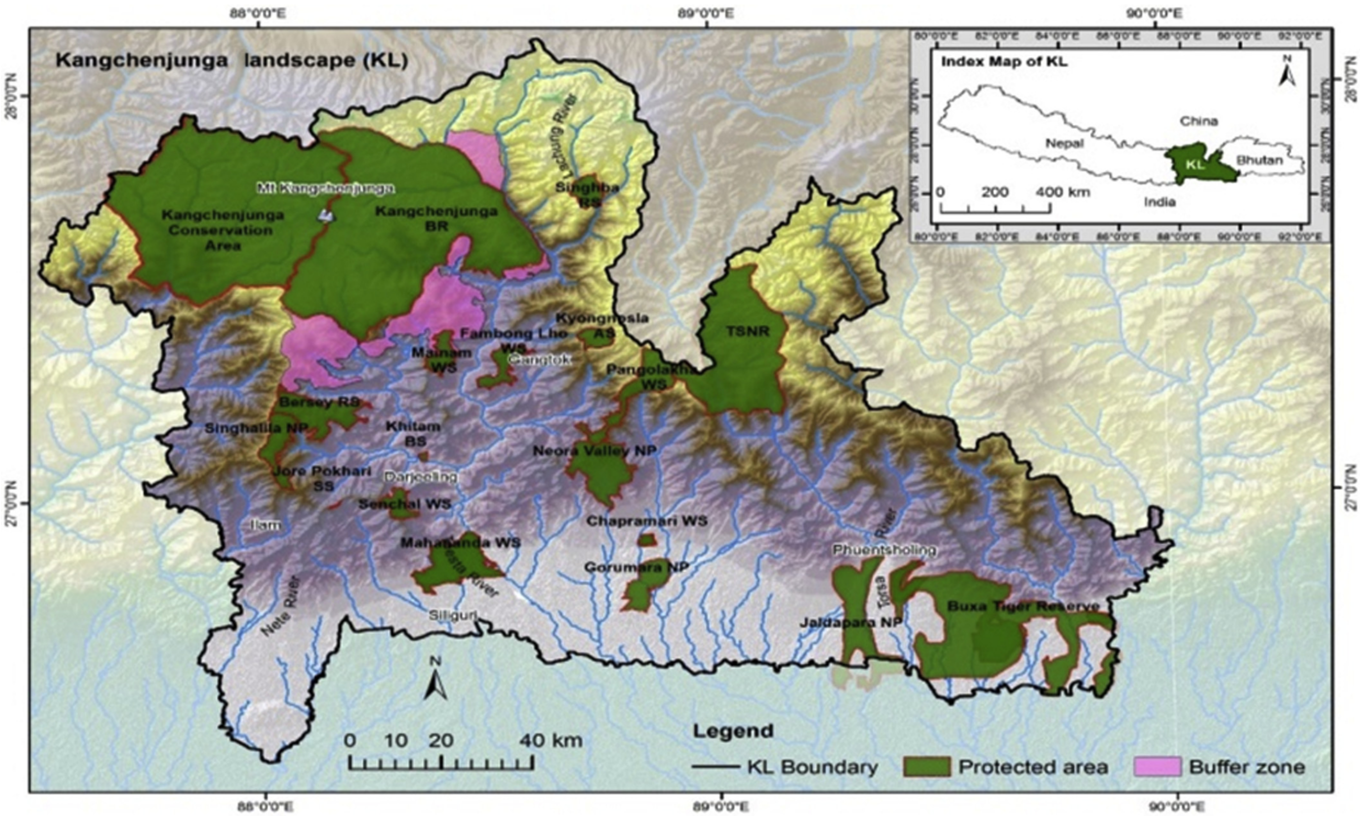

Figure 1. The Kangchenjunga landscape with protected areas.

maximus) in the lowland areas (Rana 2008). In addition, more than 4,500 species of flowering plants have been recorded in the region, with more than 500 varieties of orchid and 40 varieties of rhododendron (Chaudhary et al 2015a; Chettri et al 2008; ICIMOD et al 2015). There are many threatened and endangered plant species, including high valued medicinal plants such as the Himalayan yew (*Taxus wallichiana*), kutki (*Neopicrorhiza scrophulariflora*), and marsh orchid (*Dactylorhiza hatagirea*; Chettri et al 2008).

The KL is also home to approximately 7.2 million people of numerous ethnic and social groups (ICIMOD et al 2015). It is important, not only in terms of providing a habitat for globally significant biodiversity, but also in terms of the numerous ecosystem services that it provides to the people living within and beyond the landscape. Provisioning services (e.g. timber, fuelwood, fodder, medicinal plants, wild edibles, freshwater from the rivers originating in this area, etc.), regulating services (e.g. carbon sequestration, air and water quality regulation and purification, soil erosion control, pollination, etc.), supporting services (e.g. soil formation and nutrient cycling for farmland), and cultural services (e.g. aesthetic and recreational value for ecotourism, spirituality, and religion, etc.) are the ecosystem services that the KL provides (Chaudhary et al 2015a; Pant et al 2012). These services contribute enormously towards economic growth, local livelihoods, and commercial industries of the local communities, downstream populations, and the global community (Rai and Sundriyal 1997; Sharma et al 2008).

In the face of increasing human pressures and environmental change, the benefits provided by the landscape could act as powerful incentives to conserve nature, yet the region continues to face numerous issues that are both local and transboundary in nature (Maharana et al 2000; Pant et al 2012; Sharma and Chettri 2005; WWF 2000). The rapidly growing human population, globalization, accelerating development, including tourism, and global climate change have led to habitat degradation, biodiversity loss, decreased agricultural productivity, as well as loss of cultural heritage of the landscape (Chettri et al 2002, 2007a,b; Sharma et al 1992). Moreover, global climate change poses acute threats to the biodiversity of the Himalayan landscapes as they are rich in endemic species that have narrow and restricted ranges of distribution (Chettri et al 2010). The KL, being an important transboundary landscape designated through a consultative process (ICIMOD et al 2015), needs immediate attention in terms of effective conservation measures (Chaudhary et al 2015a; Sharma and Chettri 2005; Sharma et al 2007), and understanding the knowledge base, information gaps, and priority areas for future interventions are critical steps in making this transboundary landscape functional. Reviewing available research can serve as a starting point for much needed conservation and management interventions within a given landscape. Here, we synthesize the existing and accessible peer-reviewed literature covering biodiversity aspects in the KL to understand research trends, identify knowledge gaps, and suggest priority research areas for future biodiversity conservation and management in the landscape.

Materials and methods

The study is entirely based on literature review. While compiling the baseline information for the KL, various forms of published and unpublished documents relating to the geographically defined KL area, such as journal articles, books and book chapters, reports, conference proceedings, management and development plans, and PhD theses, were collected. We considered the geographically defined areas that include: four districts of eastern Nepal (Panchthar, Taplejung, including the Kangchenjunga Conservation Area, Ilam, and Jhapa); Darjeeling, Sikkim, and Jalpaiguri districts in India; and Haa and Paro districts, including the Jigme Khesar Strict Nature Reserve of western Bhutan. The publications were collected from the internet using the web platform 'Google Scholar'. Keywords such as "Kangchenjunga Landscape", "biodiversity", "eastern Nepal", "Bhutan", "Haa", and "Paro Dzongkhag" (districts), "Darjeeling", "Sikkim", and the names of all PAs in the KL were used to search for related articles online. Of all the collected publications (844), we considered only peer-reviewed journal articles ($n = 500$) related to biodiversity for analysis. We accept that this is not the complete list of works from the KL, but submit that this list provides a basis on which to examine research gaps and identify future priorities. A complete list of publications is available at ICIMOD's Hindu Kush-Himalayan conservation portal (ICIMOD 2015). The selected peer-reviewed articles were chronologically listed in a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) and categorized in three ways:

1. The first category was based on parts of representative countries (eastern Nepal, Darjeeling, Sikkim and Jalpaiguri districts of India, and western Bhutan) where the studies were carried out.
2. The second category was based on their publication dates, in which the studies were grouped in 10-year intervals from 1840 to 2014; this enabled us to see the research trends and patterns.
3. The third category was based on the subject focus of the research; the publications were first categorized based on the levels of biodiversity (ecosystem, species, and gene) at which the research was carried out, and were further categorized based on their sublevels (different types of ecosystems and five kingdoms of species).

Results and discussion

Geographic distribution of publication

The geographic distribution of the publications is noted with regard to the countries where the research was carried out. The majority of publications on biodiversity in the KL are from India (91%), while 5% are from Nepal and 3% from Bhutan. This is quite obvious as Darjeeling and the state of Sikkim in India make up a large part of the KL (56.3%), with l7 out of 19 PAs covering 63% of the PA coverage within the KL (Table 1). Our observations also revealed that the majority of the research works are from PAs. In addition, Darjeeling has been widely explored by naturalists during the colonization process. Likewise, the opening up of Sikkim to the outside world after its merger with India in 1975 made it accessible to travelers and researchers. The presence of academic institutions, such as the North Bengal University and the Sikkim University, in the landscape and contributions from other research and development institutions, such as the Wildlife Institute of India and the Govind Ballabh Pant Institute of Himalayan Environment and Development, also contributed to the research. In addition, the Government of India has raised research funding from 3.3 billion USD in 2004 (Jayaraman 2014) to 24 billion USD in the Twelfth Five Year Plan 2012–2017, with an average annual allocation of 4.8 billion USD (Jayaraman 2012). Furthermore, research funding and grants from international organizations, government development agencies, and foreign donors have also helped to increase the number of researchers in India, particularly in Sikkim (e.g. Chettri 2000, 2005a,b,c, 2007a,b, Singh 2000). However, only 1% of the 500 analyzed publications are of a transboundary nature and are jointly carried out in either two or three of the countries in the KL (Figure 2). This indicates that the evolution of transboundary conservation is in its nascent stages in the landscape (Chettri et al 2005a,b,c, 2007a,b, 2009; Sharma et al 2007; WWF and ICIMOD 2001; Yonzon 2000).

Temporal pattern of publications

The temporal pattern of publications in the KL is depicted in Figure 3. This study reveals that the KL attracted the attention of the scientific community as early as the 1840s (e.g. Blandford 1872; Campbell 1840; Hooker 1849; Tickell 1843). Our list of publication indicates that the first recorded study in the KL is a manuscript by Archibald Campbell, the British political agent to Sikkim and Darjeeling in the East India Company in 1840 on the *Lepchas*—the indigenous inhabitants—of Sikkim (Campbell 1840). However,

Table 1. Protected areas in the Kangchenjunga landscape.

SN	Protected area	Area (km^2)	Country	IUCN category	Major wildlife
1	Khangchendzonga Biosphere Reserve	2,620	India	–	Snow leopard, Tibetan antelope Himalayan musk deer
2	Kangchenjunga Conservation Area	2,035	Nepal	IV	Snow leopard, red panda, Himalayan black bear
3	Buxa Tiger Reserve	760	India	IV	Royal Bengal tiger, Asiatic elephant
4	Toorsa Strict Nature Reserve	651	Bhutan	Ia	Takin, red panda, Himalayan black bear
5	Jaldapara National Park	216	India	II	One horned rhinoceros, Asiatic elephant
6	Pangolakha Wildlife Sanctuary	128	India	IV	Red panda, Himalayan black bear
7	Mahananda Wildlife Sanctuary	127	India	IV	Royal Bengal tiger, Asiatic elephant
8	Barsey Rhododendron Sanctuary	104	India	IV	Red panda, Himalayan black bear
9	Neora Valley National Park	160	India	II	Royal Bengal tiger, Himalayan black bear, red panda
10	Gorumara National Park	80	India	II	One horned rhinoceros, Asiatic elephant
11	Singhalila National Park	79	India	II	Red panda, Himalayan black bear
12	Fambong Lho Wildlife Sanctuary	52	India	IV	Red panda, Himalayan black bear
13	Singhba Rhododendron Sanctuary	43	India	IV	Red panda, Himalayan black bear
14	Senchal Wildlife Sanctuary	39	India	IV	Red panda, Himalayan black bear
15	Mainam Wildlife Sanctuary	35	India	IV	Red panda, Himalayan black bear
16	Kyongnosla Alpine Sanctuary	31	India	IV	Red panda, Himalayan black bear
17	Chapramari Wildlife Sanctuary	10	India	–	One horned rhinoceros, Asiatic elephant
18	Khitam Bird Sanctuary	6	India	–	Himalayan black bear
19	Jore Pokhari Salamander Sanctuary	0.04	India	IV	Himalayan newt
	Total	7,176.04			

Source: ICIMOD, WCD, GBPIHED, RECAST, MoFSC (2015).
IUCN = International Union for the Conservation of Nature and Natural Resources.

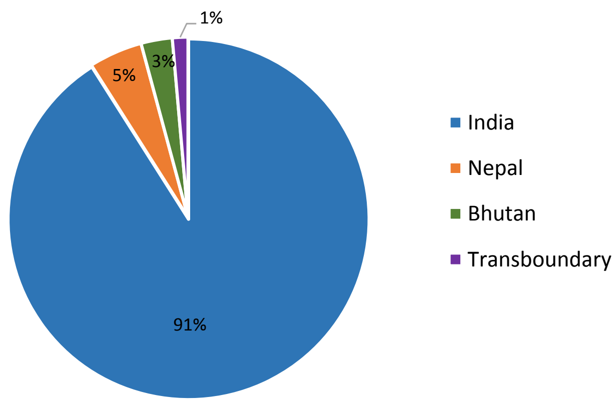

Figure 2. Geographical distribution of study sites.

considering the biodiversity and natural resource perspectives, the first scientific research carried out in the KL is by Lieutenant Tickell in 1843 about a 'tiger' of the Darjeeling hills (Tickell 1843). This was followed by the work of the notable British naturalist, Joseph Dalton Hooker, who published an account of his botanical expedition in the Kangchenjunga region in two volumes of *The Himalayan Journals* in 1854 (Hooker 1849). Along these lines, much of the earlier studies from the KL are documentation from travels and expeditions around Sikkim, e.g. rhododendrons of Sikkim-Himalaya (Hooker 1849), birds of Sikkim (Blandford 1872a), eastern and northern frontiers of independent Sikkim, with notes on zoology (Blandford 1872b), and butterflies of Sikkim (De Niceville 1881). For more than 130 years after Tickell's manuscript, publications on biodiversity and natural resources were limited (Figure 3). Between 1840 and 1980, only 61 publications were documented. The early 20th century brought in a number of research studies from Darjeeling, most of them relating to exploration of mammals and birds (e.g. Dalgliesh 1906; Khajurai 1970).

Research and documentation increased greatly after 1980; and between 1980 and the present, 88% of the 500 publications were documented. The decade between 2000 and 2010 is particularly significant, with a total of 291 articles, representing 51.2% of the total publications. This could be related to the global trend towards biodiversity focus, as illustrated by Chaudhary et al (2015b). It is to be noted that the topic 'biodiversity' became a subject of considerable global interest after 1992, as reflected in Figure 4. This could be due to a most significant event—the Convention on Biological Diversity (CBD)—a treaty which was adopted at the Earth Summit in Rio de Janeiro in June 1992 and came into force on 29 December 1993. Together with 188 member countries, Bhutan, India and Nepal became signatories to the CBD. The impact of the CBD, specifically the 'Mountain Biodiversity' decision, was widespread, with many national and international organizations—the International Centre for Integrated Mountain Development, The Mountain Institute, and the World Wildlife Fund—initiating large-scale biodiversity conservation programs in the region (Chettri et al 2007a,b; Müller-Böker and Kollmair 2000; Sharma and Chettri 2005).

Publications by subject focus

Among the 500 publications on biodiversity in the KL, 392 publications (78%) are at species level and 99 (20%) are at ecosystem level, while only nine (2%) are at genetic level (Figure 4). This could be because, in the past decades, biodiversity was viewed largely in terms of species richness, whereas most recently, biodiversity is being viewed more holistically to include genes, species and ecosystems, with each level of biological organization exhibiting characteristic and complex compositions, structures, and functions (Chaudhary et al 2015a). As a result, current biodiversity research and conservation efforts are focused on dynamic, multiscale ecological patterns and processes that sustain the full complement of biota and their supporting natural systems (e.g. Sharma and Chettri 2005; Sundriyal and Sharma 1996; Wangchuk 2007). In addition, the scant research at the genetic level could be due to very limited financial resources, lack of institutional capacity, inadequate knowledge bases, lack of accessible sophisticated technologies, and restrictive government policies to carry out genetic research in the region (Bubela and Gold 2012; Grajal 1999).

Ecosystem level research

The KL has a wide range of altitudinal variation, from tropical to alpine regions, with diverse forests and other vegetation types dominated by interesting characteristic species (Table 2). Among ecosystems, the majority of publications (45%) relate to forest ecosystems, followed by agroecosystems (37%; Figure 4). Since forests occupy 45% of the total area of the KL and harbor a high degree of biodiversity, including a large number of PAs, this could have contributed to the level of research on forests. Regarding agroecosystems, most of the publications relate to high value cash crops, e.g. large cardamom (*Amomum subulatum*; Kishore et al 2011) and areca nut (*Areca catechu*; Singh and Baranwal 1993). Since large cardamom farming is one of the major economic activities in the region which has transformed the socio-economic condition of the people, particularly in the Sikkim Himalayas and eastern Nepal, it might have attracted many researchers in this subject (Sharma et al 2002). Intercropping patterns in an agroforestry system have also been frequently assessed in the KL (Das 2013; Sharma and Purohit 1996; Singh and Baranwal 1993).

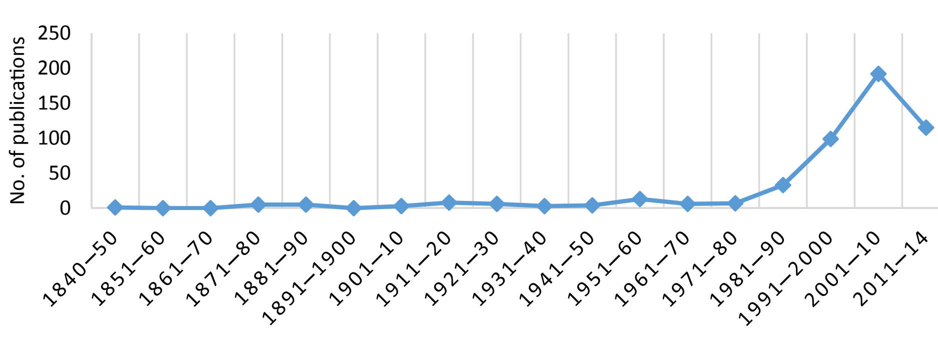

Figure 3. Temporal pattern of publications collected from the Kangchenjunga landscape.

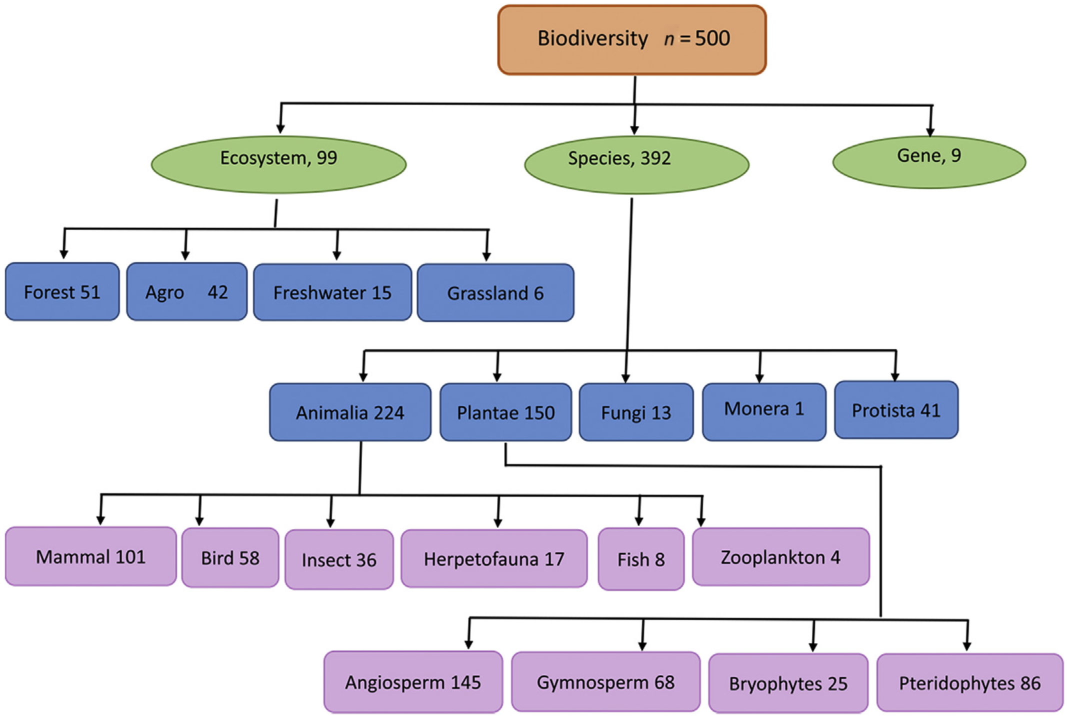

Figure 4. Number of publications in different levels of biodiversity.

The majority of research on the freshwater ecosystem is focused on hydro-ecological dynamics and the potential of ecotourism in the sacred Khecheopalri Lake in Sikkim, India (Jain et al 1999, 2000, 2005; Kumari et al 2010; Maharana et al 2000). We could access only two research manuscripts in Mai Pokhari, Nepal—the only Ramsar site in the landscape that was designated on 28 October 2008 (Rai 2009, 2013). In 2009, Rai studied the cholorophycean algae from Mai Pokhari Lake, and in 2013 compared the lentic environments of Mai Pokhari and Kechana Jheel, Jhapa, Nepal, in terms of the composition of bottom-dwelling and limnetic fauna. Although Mai Pokhari plays a functional role in the keystone ecosystem to stabilize the avian fauna, amphibian life, pond ecology, and terrestrial vegetation, it has not received considerable attention from researchers around the region and globe (DFO 2012).

Species level research

Of 392 publications on species, the majority are on the Kingdom Animalia (57.14%), followed by Plantae (38.2%). Fungi comprise only 3% of the available publications, whereas only four publications are on Monera and one on Protista (Figure 4). Among Animalia, mammals are the most studied taxa (45% of total faunal studies), with the red panda (*Ailurus fulgens*) being the most studied mammal (15% of mammal studies). Their population status, ecological distribution, and feeding habits were frequently assessed (Mahato 2004; Mallick 2010; Pradhan et al 2001). Other mammals receiving research attention are the Royal Bengal tiger (Borthakur et al 2013; Mallick 2010), clouded leopard (*Neofelis nebulosa*; Matthews 1934), wild dog (*Cuon alpinus*; Sur 1957), Asiatic elephant (*Elephas maximus*; Choudhury 1999; Sukumar 2006), Tibetan wild ass (*Equus kiang*; Ganguli-Lachungpa 1994), gaur (*Bos gaurus*; Choudhury 2002; Saini et al 2012), Himalayan goral (*Naemorhedus goral*; Bhattacharya et al 2012; Mitra 2003), ungulates (Bhowmik et al 1999; Chanchani et al 2010; Mukhopadhayay et al 2012), primates (Choudhury 2008; Mukherjee et al 1995), and rodents (Ghose and Bhattacharya 1995; Ghose and Ghosal 1969).

Following mammals, birds accounted for 25% of the total faunal studies in the KL. Interestingly, all of the documentation on birds in the KL has been recorded from India only. Most of the documentation on birds is in the form of checklists, which include many preliminary studies carried out in Sikkim and Darjeeling (e.g. Blandford 1872a, 1877; Gammie 1877; Stevens 1923a,b). Usha Ganguli-Lachungpa, an Indian ornithologist, has extensively documented various bird species from Sikkim. For instance, birds that received research attention include the black-winged kite (*Elanus caeruleus*; Ganguli-Lachungpa 1990a), ospreyo (*Pandion haliaetus*; Ganguli-Lachungpa 1990c), Brahminy duck (*Tadorna ferruginea*; Ganguli-Lachungpa 1990b), black-necked grebe (*Podiceps nigricollis*; Ganguli-Lachungpa 1992), Hodgson's frogmouth (*Batrachostomus hodgsoni*; Ganguli-Lachungpa and Lucksom 1998), black-necked crane (*Grus nigricollis*; Ganguli-Lachungpa 1998), satyr tragopan (*Tragopan satrya*; Khaling et al 1999, 2002), rusty-bellied shortwing (*Brachypteryx hyperythra*; Acharya and Vijayan 2007), and black baza (*Aviceda leuphotes*; Sivakumar and Prakash 2004). There are few ecological research studies carried out on birds. Some representative ecological research studies on birds include those by Acharya et al (2011), Chettri et al (2005b), Ganguli-Lachungpa (1990), Khaling et al (2002), and Sivakumar and Prakash (2004). There is one study on the indigenous knowledge of *Lepcha* communities for monitoring and conservation of birds, which was carried out by Acharya et al (2009) in Sikkim.

Following birds are the insects most studied in the KL. Studies on insects account for 16% of the faunal studies (i.e. 7.2% of the total studies in the KL). Among insects, most of the documentation is on butterflies. Noted entomologists like De Niceville (1881, 1885), Elwes and Gammie (1877), Maude (1949), Elwes and Moller (1888), and Sengupta et al (2014) have extensively documented butterflies from Sikkim and Darjeeling. Other than butterflies, checklists of the insects include: lamiids (Saha and Raychaudhuri 2000); wasps

Table 2. Forest types found in the Kangchenjunga landscape.

Altitudinal zone	Forest type	Characteristic species
Tropical (below 1000 m)	- Tropical riverine evergreen/deciduous forest - Tropical moist evergreen/deciduous forest - Tropical moist mixed forest - Tropical dry evergreen/deciduous forest	*Shorea robusta, Lagerstroemia parviflora, Bombax ceiba, Cycas pectinata, Dillenia pentagyna*
Subtropical (1000–2000 m)	- Subtropical riverine evergreen/deciduous forest - Subtropical moist evergreen/deciduous forest - Subtropical moist mixed forest - Subtropical dry evergreen/deciduous forest	*Schima wallichi, Castanopsis tribuloides, Macaranga pustulata, Machillus odoratissima*
Warm temperate (2000–2500 m)	- Warm temperate riverine evergreen/deciduous forest - Warm temperate moist evergreen/deciduous forest - Warm temperate moist mixed forest - Warm temperate dry evergreen/deciduous forest	*Castanopsis tribuloides, Ilex dipyrena, Quercus lamellosa, Quercus semecarpifolia, Lithocarpus pachyphylla*
Cool temperate (2500–3000 m)	- Cool temperate riverine deciduous forest - Cool temperate moist evergreen forest - Cool temperate moist mixed forest - Cool temperate dry evergreen forest	*Abies spectabilis, Betula utilis, Rhododendron arboreum, Acer* sp.
Subalpine (3000–4000 m)	- Subalpine riverine evergreen forest - Subalpine deciduous forest - Subalpine moist evergreen forest - Subalpine moist deciduous forest - Subalpine dry evergreen forest	*Abies spectabilis, Tsuga dumosa, Betula utilis, Acer* sp., *Larix griffithiana, Rhododendron barbatum, Juniperus indica*
Alpine (>4000 m)	- Alpine riverine - Alpine meadow - Alpine scrub	*Rhododendron nivium, Rosa* spp. *Juniperus indica*

Source: ICIMOD, WCD, GBPIHED, RECAST, MoFSC (2015).

(Bhattacharjee et al 2010); beetles (Raychaudhuri and Saha, 2000); mites (Roy et al 2014), and ticks (Sanyal and De 2001). There are few ecological studies on insects, including those by Chettri (2015), Das et al (2012), Ghorai and Sengupta (2014), Hazra and Chaudhuri (2004), and Raina et al (2013).

In comparison to mammals and birds, the lower taxa of fauna, especially lower vertebrates such as fish, amphibians, and reptiles, and a wide range of invertebrates, have received less priority among researchers (Figure 4). Even on a global scale, invertebrates represent more than 90% of the world's estimated 10 million animal species (Wilson 1992), yet they are underrepresented in global conservation efforts due to low interest, funding, and policy directives. For instance, each arthropod species receives 1000 times less funding for its conservation than each mammal species (Cardoso et al 2011), and a conservation status of less than 1% of the insect species described has been evaluated so far (Warren et al 2007). Generating both professional and public interest for these neglected areas of conservation science is crucial if some of these challenges are to be overcome.

Among the Kingdom Plantae, angiosperms are the most explored discipline, comprising 45% of the total. The highest number of studies on angiosperms could partly be due to their high species richness in the KL, i.e. more than 4500 species (Chaudhary et al 2015a). Pteridophytes (26%) are the second most studied discipline, whereas gymnosperms (21%) and bryophytes (8%) are comparatively less studied in the KL. Orchids and rhododendrons are the most studied taxa among angiosperms (Barman et al 2011; Yonzon et al 2012). A series of papers (Jana and Chauhan 2000; Saklani and Jain 1989; Sharma and Uniyal 2010; Yonzon et al 1981) assessed the ethnobiological aspects of plants that accounted for 57% of the total floral studies, with 38% of them relating directly to traditional knowledge on medicinal purposes of the plants (Chettri et al 2005c; Maiti et al 2003; Oli 2003; Pradhan and Badola 2008). This testifies that the KL is not only a rich biodiversity repository, but is also a region of diverse cultural and indigenous knowledge. About 18% of the studies relate to nontimber forest products and their use patterns (Chettri et al 2005c; Das 2005; Pandit et al 2004; Shankar et al 2001; Sundriyal and Sundriyal 2001).

In the group fungi, there are only 13 publications, of which eight are on lichens (Sinha and Chauhan 1996; Ram and Sinha 2010; Sinha 2004a, 2004b; Sinha and Elix 2003; Sinha and Singh 2005), whereas only two publications are on mushrooms (Das 2010; Das et al 2012) and three on other mycotaxa (Jagadeesh and Sinha 2009; Maity 2013; Saha et al 2005). The pattern of research indicates that there is a need for research in terms of species richness, abundance, habitat specificity, physiology, and phenology of fungi in the KL.

Genetic level research

There are very few studies at a genetic level, and these are confined to the population genetic structure of some flagship mammals, e.g. Asian elephants (*Elephas maximus*; Vidya et al 2005), tigers (*Panthera tigris tigris*; Borthakur et al 2013), leopard cats (*Prionailurus bengalensis*; Bashir et al 2014), and snow leopards (*Panthera uncia*; Karmacharya et al 2011), with only one study on each of these species. Similarly, there are only three genetic level studies for plants (Khan et al 2007; Sharma et al 2010; Samaddar et al 2014). The scant level of research at a genetic level could be due to very limited financial resources, lack of institutional capacity, inadequate knowledge bases, lack of accessible sophisticated technologies, and restrictive government policies to carry out genetic research in developing countries (Bubela and Gold 2012; Grajal 1999).

Research gaps and future priorities

The KL has a very diverse variation in terms of altitude and vegetation. Despite a rising number of publications on biodiversity in the KL, our literature review identifies that there is limited and skewed information on various aspects of biodiversity; this could be due to personal interests of researchers, over-emphasizing some subjects and under-prioritizing others. For instance, species level studies of some of the mammals have received high priority, whereas many others, including those on invertebrates, lacked even basic information such as a checklist of species, and whenever documented, their access is limited. Because of the dispersed

Table 3. Key research areas, research gaps, and future priorities.

Category	Key past research areas	Research gaps & future potentialities
Ecosystem	• Forest: assessment of biological corridors & connectivity; land use cover mapping; protected area management effectiveness for biodiversity conservation, community based natural resources management; impact assessment of anthropogenic pressures like resource extraction & grazing of livestock, ecological overview of PAs—Neora Valley National Park & Khangchendzonga Biosphere Reserve, India; ecotourism • Agrobiodiversity: cash crops farming particularly large cardamom & areca nut; intercropping pattern; nutrient dynamics in agroforestry system • Freshwater: ecosystem services, nutrient dynamics, & hydro-ecological analysis, e.g. Khecheopalri Lake of Sikkim, India • Grassland: composition & structure of grasslands, grazing impact on grassland, e.g. Jaldapara National Park & Khangchendzonga National Park, India	• Forest: ecosystem structure, process & functions; ecosystem services flow, use & valuation; traditional knowledge & their role in forest conservation & management, including governance; sustainable restoration & rehabilitation • Agrobiodiversity: status & contribution of agrobiodiversity in human wellbeing; traditional knowledge in management of agroecosystem; land use & cover change in relation to agroforestry practices; relationship between diversity & productivity in agrobiodiversity & its trade-off • Freshwater: identification of important freshwater ecosystems & baseline information; nutrient dynamics, hydro-ecological analysis, e.g. Mai Pokhari—only Ramsar Site in the KL; limnochemistry; primary productivity; plankton community dynamics; land cover mapping & spatio-temporal change analysis, carbon dynamics • Grassland: ecosystem health, including habitat quality, structure, productivity & phenology; nutritive status; land use & cover change mapping; livestock & grassland linkages; pastoral migration & grassland pattern; resource extraction & use pattern; dynamics of alpine ecosystem under climatic & nonclimatic impacts
Species	• Checklist/diversity of higher taxa of fauna, e.g. mammals & birds • Checklist/diversity of higher taxa of flora, e.g. angiosperms & gymnosperms • Checklist/diversity of butterflies • Ecological research for some key flora, e.g. rhododendrons & orchids • Ecological research for some charismatic mammals & birds species, e.g. red panda & satyr tragopan • Checklist/diversity of NTFPs & MAPs • Ethnobotany, particularly ethnomedicine • Human wildlife conflicts in relation to large mammals, e.g. elephants & snow leopards	• Diversity, status, & ecology of lower level taxa of fauna, e.g. fish, amphibians, reptiles & a wide range of other invertebrates • Diversity, status & ecology of bryophytes & pteridophytes • Distribution pattern & habitat specificity of endemic & threatened species of flora & fauna • Interaction or relationship between species diversity & ecosystem functions • Invasive species & their potentially ecological impacts • Diversity & functional roles of mushrooms, lichens, bacteria & cyanobacteria in ecosystems • Traditional knowledge for monitoring & conservation of species • Geospatial analysis of human wildlife conflicts
Gene	• Population genetic structure of large mammals, e.g. rhinos, elephants, snow leopards, & tigers	• Gene pool of agrobiodiversity • Genetic analysis & mapping of endemic & threatened species of flora & fauna • Factors influencing genetic diversity of the species • Evolutionary genetics of invasive species • Plants & animal diseases

KL = Kangchenjunga landscape; MAPs = Medicinal and Aromatic Plants; NTFP = nontimber forest products; PA = protected area.

availability of literature in various sources (such as libraries) in the form of unpublished reports, private collections, etc., not many are easily accessible. Therefore, it is important to develop a bibliography, a metadata of research, and provide a platform to make such grey literature accessible. A functional database on all subjects could be an important first step towards effective management of biodiversity in the landscape.

Based on the findings, we have tabulated specific existing research, including gaps and priorities for the future using three levels of biodiversity (Table 3). We observed that the existing literature on priority research areas is also far from complete. The ecology of major ecosystems, the distribution and ecology of many threatened species with global significance are limited to few geographical pockets. There is a major gap in research investment towards, and prioritization of, lower taxa, including invertebrates and microbes. Many aspects of evolving science, such as ecosystem dynamics, functions and service flow, contribution of ecosystems, species, and even genes towards human development, could be embedded at ecosystem, species and genetic levels for future research. In addition, some of the key ecosystems, such as forests, wetlands, and grasslands, could be focused more towards a better understanding of these ecosystems as service providers, as well as representing an important repository of biodiversity.

As the landscape is shared by three countries, regional cooperation for effective science and practices through collaborative efforts have been emphasized to address the above-mentioned research gap (Rastogi et al 1997; CEPF 2005; WWF and ICIMOD 2001). It is imperative to have adequate human resources and funding for research to guide policies for effective management of the biodiversity at a landscape level. More importantly, for any management interventions, the resource governance system, both at local and regional (landscape) levels, needs to be strengthened through joint research, pilot demonstration, and development of information and data-sharing platforms as suggested by Sharma et al (2007). These future interventions should hasten the generic understanding of the knowledge gaps and priorities. Therefore, to understand the dynamic and complex nature of the ecosystems and the interlinkages therein, it is imperative to have a collaborative framework and strategies for long-term research and monitoring for better management of the global biodiversity assets provided by this rich transboundary landscape (Chettri et al 2015).

Conclusion

In this paper, we have traced the history of biodiversity research in the KL, showing how it is distributed in the region, and how it has grown over time and evolved in different ways. We have shown, for example, that the landscape has a long history of research since the 1840s, which increased remarkably after the 1980s. It has evolved from checklists of charismatic mammal and bird species to advanced ecological research, oriented towards long-term biodiversity conservation and management. Our paper also identifies the key areas researched, knowledge gaps, and future research priorities. It demonstrates that there is eminent research at the species level of biodiversity, followed by the ecosystem level. However, there is relatively less research focusing on lower taxa and genetic levels. At a species level, research on fauna (especially mammals) and flora (especially angiosperms) are most notable, but with major gaps in systematic research on their ecology, whereas microbes and invertebrates other than butterflies appear to be neglected. Also, there is a dearth of information on other groups of species, such as fungi, monera, and protists. Similarly, freshwater habitats and grasslands are poorly researched compared with forest ecosystems. There is a need for long-term data and monitoring mechanisms to allow interpretation of the changes occurring in the landscape, particularly in light of global climate change, that may be affecting phenology, distribution of species, and emergence of new pests and diseases, among others. It is therefore important that a wide array of academic disciplines joins in the efforts to bridge the existing knowledge gaps in the landscape.

Acknowledgments

The authors would like to express their gratitude to Dr David Molden, Director General of ICIMOD, for his inspiration and support. The continuous support and commitment from ICIMOD's eight regional member countries is also acknowledged, as is the support of the Austrian Development Agency and the German Federal Ministry for Economic Cooperation and Development through its German Agency for International Cooperation, which made this publication possible.

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