Assessment of Bees in Agro Forestry in Kangsabati South Forest Division, Purulia, West Bengal

Thesis submitted for the award of the degree of

Doctor of Philosophy

in

WILDLIFE SCIENCE

by

PALLABI DAS

to

Saurashtra University

Rajkot- 360005 (Gujarat)

Under the supervision of

Dr. V.P. Uniyal , Supervisor

Dr. Kailash Chandra, Co-Supervisor

2024

Citation:

Das, P. (2024). Assessment of Bees in Agro Forestry in Kangsabati South Forest Division, Purulia, West Bengal. Ph.D. Thesis. Wildlife Institute of India, Dehradun, India and Saurashtra University, Rajkot, India.

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

DECLARATION

I, hereby, declare that the work conducted under this thesis titled "**Assessment of Bees in Agro Forestry in Kangsabati South Forest Division, Purulia, West Bengal**" is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Doctor of Philosophy in Wildlife Science** to the **Saurashtra University, Rajkot (Gujarat)**. This research work has been carried out under the guidance and supervision of Dr. V.P. Uniyal of Wildlife Institute of India, Dehradun and Dr. Kailash Chandra of Zoological Survey of India. The work has not formed the basis for the award of any other degree, diploma or any other qualification. I also declare that the thesis embodies my own work, analysis, observation, understanding and the particulars given in it are true to the best of my knowledge.

Pallabi Das
(PALLABI DAS)
Place: DEHRADUN
Date:

(Dr. V.P. UNIYAL)
Supervisor

(Dr. Kailash Chandra)
Co-supervisor

पत्रपेटी सं0 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. :+91–135–2640114, 2640115, 2646100 फैक्स : 0135–2640117
EPABX : +91-135-2640114, 2640115, 2646100 Fax: 0135-2640117
ई–मेल / E-mail : wii@wii.gov.in वेब / Website: www.wii.gov.in

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

CERTIFICATE

This is to certify that **Miss PALLABI DAS** thesis, " **Assessment of Bees in Agro Forestry in Kangsabati South Forest Division, Purulia, West Bengal,"** submitted for the degree of **Doctor of Philosophy in Wildlife Science at Saurashtra University, Rajkot, Gujarat**, embodies original research work carried under our guidance and supervision.

Miss PALLABI DAS has researched on this thesis for more than six terms under our supervision and guidance. The work presented in this thesis has not been submitted for any other degree. It meets all of the specifications stated forth in the ordinances of Saurashtra University in Rajkot, Gujarat, and the Wildlife Institute of India.

Forwarded by:

Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. V.P. Uniyal)
Supervisor

(Dr. Kailash Chandra)
Co-supervisor

Date:
Place: Dehradun

पत्रपेटी सं0 18, चन्द्रबनी, देहरादून – 248 001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun - 248 001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स. :+91–135–2640114, 2640115, 2646100 फैक्स : 0135–2640117
EPABX : +91-135-2640114, 2640115, 2646100 Fax: 0135-2640117
ई–मेल / E-mail : wii@wii.gov.in वेब / Website: www.wii.gov.in

SAURASHTRA UNIVERSITY
P.G.T.R Section
Main Office, First Floor
University Road
Rajkot - 360 005 (Gujarat)
Phone No. : 2578501
Fax : (0281)2856983
www.saurashtrauniversity.edu

Accredited Grade 'A' by NAAC

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I certify that the research work was appreciated by all who were present, and the comments made by the faculty and researchers have been appropriately included in the thesis.

(Dr. Ruchi Badola)
Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

(Dr. V.P. UNIYAL)
Supervisor

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भारतीय वन्यजीव संस्थान, देहरादून
Wildlife Institute of India, Dehradun

(Dr. Ruchi Badola)
Dean
Faculty of Wildlife Science

संकायाध्यक्ष / Dean
भारतीय वन्यजीव संस्थान
WILDLIFE INSTITUTE OF INDIA
देहरादून / Dehradun

पत्रपेटी सं0 18, चन्द्रबनी, देहरादून – 248001, उत्तराखण्ड, भारत
Post Box No. 18, Chandrabani, Dehradun – 248001, Uttarakhand, INDIA
ई.पी.ए.बी.एक्स : +91-135-2640114, 2640115, 2646100 फैक्स : 0135-2640117
EPABX : +91-135-2640114, 2640115, 2646100; Fax : 0135-2640117;
ई–मेल / E-mail: wii@wii.gov.in, वेब / website: www.wii.gov.in

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Acknowledgements

The enriching journey of my Ph.D. was only sufficient with several people's invaluable guidance and directions. I take this opportunity to express my gratitude to my supervisor, Dr. V.P. Uniyal (Former Scientist G) Wildlife Institute of India, for his support and patience throughout the thesis work. I am also thankful to my co-supervisor, Dr. Kailash Chandra (Former Director) Zoological Survey of India, for his guidance and support.

I want to thank the Wildlife Institute of India (WII), Dehradun, and Zoological Survey of India (ZSI), Kolkata, for all the support and invaluable learning opportunities that eventually impacted my career. I extend my heartfelt gratitude to the Director, Mr. Virendra Tiwari, and Dean, Dr. Ruchi Badola, Wildlife Institute of India. I sincerely thank Prof. Qamar Qureshi and Dr. K. Ramesh for their suggestions and guidance on my Ph.D. thesis. Also, I want to convey my gratitude to Mr. M.M. Uniyal, I.T., R.S. & G.I.S. Cell, Library, Academic section, Administrative section, and Santosh Bhaiya of W.I.I., Dehradun.

My acknowledgments would be incomplete without thanking the Hymenoptera Section, ZSI., Kolkata, Dr. S.I. Kazmi, and especially Dr. Ramesh Kumar for helping me to learn bee taxonomy in my initial days. I am grateful to Bhaswati Mazumder, Sayan Sarder, Sudipto Sahoo, and Lingaraj Parida for making my Z.S.I. days memorable. I am incredibly thankful to Dr. Jagdish Saini, Department of Zoology, Allahabad University. With your contribution to my thesis, I can make it to the finish line.

My deepest regards to the West Bengal Forest Department, Kangsabati South Forest Department, West Bengal, especially the D.F.O., for permitting the research work. I want to thank the Rangers of the division, Mr. Hirak Sinha, Mr. Binoy Mahato, Mr. Supriyo Sarker, and the forest guards for their unwavering support during my survey days. I would like to thank the farmers for allowing me to conduct my study on their agricultural land and my field assistants, Sushanta Mahato, Sadhan Barui, and Indro Mahato, for their support during the field survey. For various reasons, I am thankful to

Subhash da, Arun da, Chotu da, Subodh Mahato, Suresh Mondal, Rakhal Mahato, Sadhan Barui, and Magaram Mandal. Not least, I am incredibly grateful to Dr. Asitava Chatterjee and Mrs. Baishali Chatterjee for their immense support; without their support, it would have been impossible to conduct the study.

I thank Dr. Shivam Shrotriya, Vandana, Kamna, Dipamoni, Prasad, Tushar, and Pranay for their expertise in my analysis. I am grateful to Dr. Preeti Virkar, Dr. Vandana Mehrwar, Dr. Mona Chauhan, Shuvendu Das, and my fellow lab mates for their support and guidance.

Further, I express my gratitude to my teachers, Mr. Tapas Roy, Dr. Ranu Naskar, Dr. Subir Dasgupta, and Dr. Taraknath Khan, who constantly motivated and kept faith in me in the initial days of my student life and career. Also, I express my gratitude to my friends Advt. Tiyasa Biswas, Anirban Roy, Aniket Bagchi, Dr. Das, Neelam Sharma who always remain my moral support. I want to thank my family members. Last but not least, I want to convey my gratitude to all those whose names may have been overlooked but with whose assistance my thesis was completed. Ultimately, I am grateful to the almighty for always supporting me in overcoming all the obstacles smoothly and successfully achieving this journey.

Pallabi Das

Summary

1. Introduction

Plant pollinator interactions have evolved through diffuse co-evolution, representations of relation between plants and animal species, where bees play a crucial role in preserving native plants' diversity and their reproduction success (Ollerton et al., 2011). Bees are winged insects in the Superfamily Apoidea from the Order Hymenoptera. Bees are found worldwide, with diverse communities in warm, temperate Xeric areas. Bee diversity in the forest was supported by more resources, such as food and nesting places, which support their diversity (Nery et al., 2018). Agroforestry is now recognized as a significant ecosystem, particularly in tropical countries, and combining crops with diverse plant species can increase insect diversity. The positive interaction between trees and crops was maximized, and with this strategy, preserving pollinators and increasing pollinator-dependent crop yield can be initiated (Chatterjee et al., 2020). Over 90% of the world's leading crops are pollinated by bees (Potts et al., 2016). non-*Apis* species were more pollinator-friendly than honey bees (Javorek et al., 2002; Kreman et al., 2002). Pollination in farmlands is positively correlated with native bee diversity and wild floral diversity (Mackenzie & Winston, 1984; Kremen et al., 2004; Morandin, 2007). Conservation strategies should incorporate niche-based differences by emphasizing the restoration and preservation of natural habitats rich in zygomorphic and actinomorphic flowers, as Sydenham et al. (2022) suggested. Pollination's economic, social, and environmental significance as an Ecosystem System (E.S.) is irreplaceable. One critical ecosystem service, based on the interaction between plants and pollinators, is the production of fruits, referred to as "proto-cooperation." Plant flowers are visited by pollinators to obtain their food (nectar and pollen) and facilitate the process of pollination.

2. Research questions and objectives of the study

This research intended to investigate the bee community composition in the agroforestry ecosystem, focusing on the impact of anthropogenic activities on pollinator

diversity and ecosystem services of wild bees. This study made an effort to compile a list of bee species in both agriculture and forest ecosystems and their interaction with plant functional groups in the study site.

3. Study area

The study was conducted in Kangsabati South Forest Division (KSFD) in Purulia, West Bengal. The topography is undulating, with hilly terrain in the western and southern parts, which are extensions of the Chotanagpur Plateau, one of the Earth's oldest landmasses, and the forest range of Chandil Dalma Elephant Reserve. This region is predominantly characterized by sacred groves, where native flora and fauna are naturally preserved in traditional rules and beliefs. Additionally, uniqueness and biogeographical significance are attributed to this region because, in the past, this plateau was connected to the Satpura Hills and the Eastern Himalayas, allowing species to move between these ranges (Hora, 1949). Despite its exceptional diversity and agricultural dominance, it faces anthropogenic threats such as deforestation, habit fragmentation, urbanization, forest fire, mining industries, etc. The agrodiversity of this region is increasingly threatened by the overuse of fertilizers, herbicides, and inorganic pesticides. KSFD is located in the southern part of the Purulia district in the western portion of West Bengal. The forest division spans 310.27 square Km/ 28559.30 ha areas and is between 23010'0 "- 22050'00" North latitude and 86040'0"- 8700'0" East longitudes. Six forest ranges are comprised within it: Bandwan-I, Bandwan-II, Jamuna, Manbazar-I, Manbazar-II, and Barabazar. According to biogeography, this division is covered by a Dry Deciduous Forest (5B/C 1C) and represents Peninsula Chhotonagpur (Zone 06B). All six ranges of KSFD were sampled; however, due to widespread human habitation and deforestation, the extreme northern portion of the division was not sampled.

4. Methodology

Extensive field research was conducted from February 2020 to April 2023. Field surveys were suspended due to lockdown and some restrictions were implemented by the Indian Government. The study involved 95 survey sites across 63 agriculture sites and 32 forest patches. Based on dominant cultivation, nine crops were selected. Bees were observed three times, following methodologies like belt transect, focal observation, and colored pan traps (UV-bright paints applied to pan traps). A standard identification key was used to classify bees into morphospecies and families. A socio-economic survey was conducted among residents of all existing economic classes, and a bee album was made to identify the known species of bees in the population under study.

5. The diversity of bee pollinators and the effect of agriculture on pollinator diversity.

In the study, 25 species were successfully documented from three habitats: mixed forest, Sal forest, and agricultural landscape. An average of 96.3% of bee species were successfully reported through total sampling. Bee species of three families- Apidae (61%), Halictidae (31%), and Megachilidae (8%) - were recorded. The agricultural landscape was found to have the most diverse and more prosperous ecosystem for bee species than natural habitats (mixed and Sal forest), with high evenness in bee species distribution. Low bee diversity and low evenness were observed in the mixed forests because of differences in plant species distribution (variation in flowering period and floral pattern). In contrast, modest diversity and evenness were maintained in the Sal forest due to the dominance of one plant species. Modest dissimilarities in bee community composition existed between mixed and Sal forests due to sharing almost identical environmental characteristics and ecosystem functions. A diverse community of bee species interacting with crops was observed in the agricultural landscape, with moderate Shannon diversity index values. High diversity index values were recorded for crops like green gram, ridge gourd, eggplant, and tomato. High evenness values were also observed in these crops, suggesting a relatively even distribution of various bee species within those crops. The bee diversity in crops like sunflower and sesame was moderate. A high degree of dissimilarity was maintained between tomato, eggplant, and all other crops. In contrast, an average level of dissimilarity (33.4%) suggested that a low to moderate portion of the bee species found in the agriculture landscape were shared among these crops, and high similarities were observed among two oil seed crops, i.e., mustard and sunflower. Meteorological parameters like temperature (positive), humidity (positive), wind speed (negative), and sky conditions (negative) had moderate influences on the foraging pattern as well as the abundance of bees. The study found that the majority of residents in the study area were below the poverty level and an Indigenous community, relying on forest for firewood and non-timber forest product (NTFP). Agriculture practices were prevalent, with migrant labor being a significant trend. The agricultural practice was not considered eco-friendly, and excessive pesticides were used. The study also found that less than 50% of the respondents were familiar with bees. Subsistent and unskilled agriculture was practiced by less literate farmers, leading to land degradation and wasteland. The study highlights the need for eco-friendly agriculture practices and the degradation of natural habitats due to human activities.

6. Ecosystem services of wild bees in the agroecosystem in contrast with anthropogenic activities.

The relationship between bee species diversity and the stability of ecosystem service (E.S.) was investigated in this study. The study categorized bee communities into social and wild bees, and interpolated (IDW) diversity maps were generated for each survey site. Moderate spatial distribution of bee species diversity was noticed; however, contrary to high diversity observed in sites 43, 46, and 59, especially for social and wild bees. In sites 47 and 49, cumulative moderate bee diversity was observed, but these sites showed high diversity for social bees and low diversity for wild bees. Few sites like 25, 57, 60, and 61 exhibited high diversity of social bees, but surprisingly, wild and overall bee diversity was low. In site 40, the diversity of wild bees and overall bee communities was moderately distributed, but the diversity index for social bees was unexpectedly low. The decline in population and diversity of bees' is observed gradually due to the influence of several anthropogenic activities, as demonstrated by several past studies. A low to slightly intermediate anthropogenic impact, mainly for agricultural landscapes, was noticed through the Human Footprint Index (HFI) map of KSFD. The negligible HFI value in some areas was explained by the forest patches of the area.

However, negligible bee diversity for social and wild bees was associated with very high HFI value zones in the surveyed area. Contradictory results were observed within the intermediate anthropogenic pressure zones, such as moderate diversity of social bees in sites 5, 10, 19, and 26 and a high diversity index of wild bees in sites 25, 34, 59, and 60.

A moderate degree of diversity of wild bees was spotted across the study area. As low to slightly intermediate anthropogenic impacts were observed throughout the study zone, it is concluded that the distribution of wild bees negatively correlated with anthropogenic impacts. As a consequence, the ecosystem services of wild bees in crop pollination were adversely affected.

7. Non-crops' role in sustaining the pollen networks.

The study aimed to assess the plant-pollinator networks, which are composed of flowering plant species and bees as pollinators. The floral functional group remained constant, considering how network structures responded to natural bee communities. The most common structure pattern in mutualistic networks was nestedness, with 60-70% of nestedness in the plant-animal mutualistic networks illustrated by the relative abundance. Plant-pollinator interaction was evaluated by connectance, with Most bees interacting with yellow pan traps with strong weighted interaction. The study found a high abundance of bees in *Butea monosperma*, a yellowish-red flower known as the "Flame of the forest." Bees mostly interacted with yellow-colored wildflowers like *Falcourtia indica*, *Tamarindus indica*, *Buchanania lanzan*, *Cleistanthus collinus*, and *Terminalia tomentosa*. *Megachile hera* only interacted with the white pantrap; Nomia *elliotii* was collected from the yellow pantrap. *Lassioglossum* sp. was the most dominant species and interacted with three colored pan traps; expect a similar trend would be observed in wildflowers. In the study, most flowering wild plants like *Cleistanthus collinus*, *Buchanania lanzan*, *Terminalia tomentosa*, and *Butea monosperma* were moderately interacted with by specialized bee species like *Xylocopa fenestrata*, *Megachile lanata*, and *Amegilla zonata*, primarily by a specific subset of bee species. *Apis dorsata* was highly dependent on *Shorea robusta* and *Butea monosperma*. However, other bee species, such as *Megachile lanata*, *Amegilla* *zonata*, *Nomia elliotii*, and *Xylocopa fenestrata*, also interacted with native flowering plants for nectar or pollen. However, *Tetragonula iridipennis* was found to have intense interactions with other bee species in all plants except *Shorea robusta*. *Shorea robusta* was strongly associated with *Apis* bees. *Apis florea* didn't encounter complex interactions with other bee species in any plant-pollinator network, while *Apis cerana* faced tension with bee communities within the same ecological network. The real network was slightly different from the hypothetical network, with all interactions occurring moderately in a sub-settled manner. *Tetragonula iridipennis* and *Apis dorsata* were the study area's most generalist pollinators or key bee species in this plant-pollinator network. The protruding role of crop plants in sustaining pollen networks and bee populations was revealed, and as an outcome, crop plants indirectly play a role in crop production.

8. Concluding remarks and key recommendations

The doctoral thesis documented and identified 25 bee species, including 21 wild and rare species, in various habitats in KSFD, revealing a diverse bee population indicating intense crop pollination. Non-crop/ wild plants are beneficial for bees due to their extended flowering period, which provides insufficient rewards like pollen and nectar in context to crops. Forage resources and appropriate nesting sites for bees are fed by natural habitats. However, habitat alteration and deforestation were prominently observed in the study area's HFI map (2009) caused by extensive agricultural practices, supported by the present socio-economic survey, leading to land use and land cover changes. This could affect bee communities and lead to the decline of bee species. Specialist bee species depend on specific plants for pollen and nectar, and the loss of these plants can affect their survival and disrupt the plant-pollinator network. Non-crop/ wild plants play a significant role in sustaining pollen networks, benefitting crop pollination. Protecting wild plant species and natural habitats is essential to meet future food production needs. To maintain and increase the bee population, the forest department requires the cultivation of tree saplings, and also, to maintain biodiversity and ecosystem function, the government sector must take action to reduce habitat alteration, deforestation, and forest fires. Small-scale businesses from NTFPs or handicrafts involving women and older people should be initiated, supporting economically, especially for residents under the poverty level, to reduce their dependency on firewood. Drastic changes in the ecosystem need to be overcome and scientific agriculture practices should be included by the state agriculture department and local NGOs, such as promoting Integrated Pest Management (IPM), supporting organic farming, reducing inorganic pesticide usage, and recognizing pollination as an essential element in agricultural extensions services. Awareness programs and campaigns for pollinator-friendly agriculture practices are also needed. Indigenous knowledge-based agriculture practices with a scientific approach and bee culture of honey bees and wild bees can quickly restore an abundance of diverse pollinators. This research work benefits scholars, scientists, and R&D agents, and further investigation and monitoring of pollinators in KSFD of Purulia district, West Bengal, can be conducted.

Chapter - 1

Introduction

"If the bee disappeared off the surface of the globe, then man would have only four years of life left. No more bees, no more pollination, no more plants, no more animals, no more man." *- Albert Einstein*

1.1. Overview

Bees are animal that move about on bright, pleasant days and visit attracting flowers. Bees are winged insects in the Superfamily Apoidea. Except for Antarctica, bees are found on all continents. Bees feed on pollen and nectar; most pollen is used for their larvae. They are intimately related to wasps and ants, are of monophyletic lineage, and are considered Clade Anthophila. The main beneficial activity of bees in the aspect of human benefits is their pollination of natural wildflowers and crop production. The role of bees as pollinators is equally vital both commercially and ecologically. They carry pollen between plants of different sexes to fertilize them, which indirectly helps plants reproduce and increase their genetic diversity.

Pollination has a long evolutionary history; most plant-pollinator interactions have passed through a diffuse co-evolution. Around 250-200 million years ago, the first terrestrial plants were thought to have evolved to develop the ability to attract animals to transport pollen grains; the first fossil gymnosperms show evidence of animal pollination, probably flies and beetles. Many examples of co-evolutionary characteristics between plants and pollinators have specialized in some plant-pollinator interactions. Scientific studies on pollination have been known to have a lengthy background that stretches back to the Greek philosopher Theophrastus (around 320 BC). Later, Charles Darwin also contributed to pollination in orchids (Darwin, 1862) and reproduction in plants (1876), which may be the starting point for present-day research.

Bee-dependent plants are rich in desertic and xeric scrub areas, and these plants play a crucial role in preventing erosion and providing food for wildlife. Thus, the conservation of many habitats depends on preserving the bee population; if bees disappear, the reproduction of many flora will be hampered (Mischner, 2007). Many cultivated plants are dependent on bee pollination, which humans immediately need. Humans also passively rely on bees for horticulture, honey, and bee wax production.

1.2. Evolution and Biogeography of the Bees

The Order Hymenoptera includes subgroups that can function as pollinators, particularly the Aculeata, which, in addition to the bees, includes ants, stinging wasps, digger wasps, spider wasps, mason wasps, and cuckoo wasps. Many species in these groups regularly occur in flowers. The name Hymenoptera symbolizes to the wings of the insects, but the original derivation is unclear. The distinctive characteristic of this order is that a series of hooks connect the hind and fore wings. The cladogram of external relationships, established on a 2008 protein and DNA analysis, exhibits the order as a clade, most similarly related to endopterygota orders, along with the Diptera (true flies) and Lepidoptera (butterflies and moths). The bees and sphecoid wasps are counted as allied groups and united as the Superfamily Apoidea. Bees evolved from a group of Sphyciform wasps in the early Cretaceous period (Grimaldi & Engel, 2005). Primitive solitary bees began their journey to sociality in the late Cretaceous period. A wide range of transitional stages of social evolution can be observed between solitary bees and social bees, which involves living in communal nesting, quasi-social, semi-social, sub-social, and primitive eusocial (O'Toole & Raw, 1999).

Bees are a monophyletic group that constitutes around 20,000 bee species worldwide that have been described. Seven families are found worldwide; only two families- Halictidae and Apidae show social development. The five families- Andrenidae, Mellitidae, Colletidae, Megachilidae, and Stenotretidae- remain solitary bees. Bees are grouped based on the evolution of their societal behavior. Solitary bees display different types of nesting behavior; these are-

Carder bees – These bees select their nest in ready-made cavities of the plant; they line it with the plant's fibers.

Carpenter bees – Bees made nests in the wooden substances using their strong mandibles.

Cleptoparasitic bees – These bees are parasitic; they lay eggs in the nests of host bees.

Leafcutter bees – These species made their nest with leafy materials, and mostly these are abandoned by beetles.

Masked bees – A type of mining bees that have distinct white or yellow markings on their face. These bees line the nest cells with secretions from the Dufour's gland or the enlarged thoracic salivary glands.

Mason bees - Nests of these species are built in existing cavities, such as cracks in wood and rock or holes into the soft piths of the stems. In addition, these bees use mud, resin, dung leaves, petals, wood chips, pebbles, twigs, etc. to line their cavities.

Miner bees - Some bee species burrow the earth to build nests. In the process, the nest's opening has a small mound around it.

Termite nesting bees – These bee species built their nests in termite mounds.

Bees cover various distributions, from the cold Arctic tundra to the world's semi-arid regions. Warm, temperate Xeric regions support diverse bee communities such as the southwestern United States of America, northern Argentina, the Mediterranean area, southern Africa, dry steppes in Central Asia, and semi-arid scrublands of parts of Australia. Most social bees are abundant in tropical regions that afford floral resources yearly. These warm temperate areas are the origin of the ancient bees. The last bee abundance is observed in the frigid regions, moist tropical (Old World), Tropical grasslands, savanna, cool temperate Xeric, and Extreme desserts. Bees' distribution on the islands may result from drifting wooden pieces from the nearby mainland (O, Toole & Raw, 1999; Michener, 2007; Michener, 1974).

1.3. Plant Pollinator relationship

The interaction between bees and flowering plants is a mutualism; the plants have their reproductive gametes (pollen grains) dispersed by bees, which visit their flowers to enable fertilization and reproduction, and the bees are rewarded mainly in the form of nectar and pollen (Willmer, 2011). This interaction is called pollination, and it studies pollination ecology or pollination biology. In tropical ecosystems, other insects (e.g., butterflies, beetles), birds (e.g., sunbirds, hummingbirds), bats, and a few other mammals (e.g., lemurs) are also important pollinators. Pollination can be defined as a flower visitor who effectively transports pollen from stamens to stigmas. All flower-visiting creatures are, however, not pollinators. Some, for example, are too small to contact with the reproductive parts of the flower (anthers with pollen and stigmas).

Consequently, they do not transport pollen but function like parasites on the mutualism between flowering plants and their real pollinators. Some bees are Oligoleges, meaning genera or species-specific plant visitors, but most are polylectic or generalized. Most cultivated and wild plants depend, at least in part, on animal vectors, known as pollinators, to transfer pollen. Pollinators visit flowers primarily to collect or feed on nectar and pollen. Pollinators comprise a diverse group of animals like- insects, which include bees, some species of flies, butterflies, moths, beetles, wasps, weevils, thrips, ants, midges, and higher animals like bats, birds, and primates. Bees are the primary pollinators and roughly cover 90% of the world's plant population (Winfree, 2010). Thousands of plants are dependent on pollinator interactions; among them, many crops are pollinator-dependent.

Approximately 308,000 species (87.5%) of the world's flowering wild plants depend on animal pollination for sexual reproduction, ranging from 78% in temperate zone to 94% in tropical zone communities. The solitary bees are often more specialized to specific species of flowering plants than the social bees and synchronize their flight period with the blooming of the plants. In bees, the length of the tongue represents an essential function of acquiring food resources and efficient pollination (Rodriquez-Girones & Landres, 2008; Harder, 1983); even bees become specialists and generalists for a particular floral partner, and in return, they develop a symbiotic relationship (Stang et al., 2009; Vazquez et al., 2009).

1.4 Crop pollination

Bees play a significant role as pollinators in agriculture, especially for economically significant crops, and serve as a fundamental pillar for crop yield and quality. Most of the essential cash crops (coffee, cocoa, almond, etc.) of the world benefit from pollinators regarding yields and quality (Potts et al., 2016). Animal pollinators contribute 35% of global food production. Klein et al. (2006) evaluated that about 70% of crops (87 of the 124 main crops) in 200 countries used globally in the human diet are pollinator-dependent. Farmers widely managed honey bees or *Apis* bees for crop production. Not only are honey bees a significant bee species, but native and solitary bees are also substantial for human well-being. non-*Apis* bees pollinated many crops better than *Apis* bees (Winfree, 2010). A diverse community of bees provides more effective and stable crop pollination (Potts et al., 2016). Native and solitary bees can enhance the efficiency of honey bees (Greenleaf & Kremen, 2006; Chagnon et al., 1993). Unmanaged non-*Apis* bees can fully pollinate crops in some agricultural conditions (Winfree et al., 2007; Kremen et al., 2002; Klein et al., 2003; Klein et al., 2003). Pollinator loss can decrease crop production by 90% in 12% of the leading global crops; even around 28% would lose 40-90% of the production (Potts et al., 2016). Also, native bees perform their pollination services in colder, windier weather conditions (Brittain et al., 2013); even individual native bee is more efficient pollinators than honey bees for particular crops (Tepedino, 1981; Bosch and Kemp, 2001; Javorek et al., 2002; Garibaldi et al., 2013). In temperate regions, bumble bees can tolerate cold weather, and their body hairs can carry more pollens than honey bees, which makes them popular pollinators in the agricultural industry (Free & Williams, 1972; Kendall & Solomon, 1973; Corbet et al., 1993).

These crops provide 30% of the human food (Kearns & Inouye, 1997). Many cash crops' yield and quality directly depend on pollinators. Various studies showed that yields of many crops decline due to the local declines and lower stability of the diverse bee community. Bhattacharya & Basu (2018) observed eggplant yielded 50% less fruit in a pollinator-excluded environment. Many vegetables, fruit, oil, and nut crops provide the human diet with vitamins, micronutrients, and minerals. Diverse bee communities more effectively maintain stable crop pollination than any single species; yields of many crops indicate local declines and lower stability when pollinator communities lack a well-established variety of species community. Animal pollination plays an essential role in regulating ecosystem services in nature. Some specific actions, like ecological intensification, can improve the pollinator population.

Intercropping, crop rotation, creating flower-rich field margins, agroforestry, and restoring and maintaining the native wildflowers' habitat extend the pollination services to foster a diverse pollinator community through ecological intensification (Potts et al., 2016).

1.5 Agroforestry ecosystem

Agroforestry is a distinct land use system combining forestry, agricultural, horticulture, and animal husbandry subsystems and practices (Fig. 1.2.). Agroforestry integrates trees with crops to reduce risk and increase total productivity. Agroforestry systems are stable and sustainable practices with greater diversity than monoculture. Integration of trees into agricultural systems helps use sunlight, moisture, and plant nutrients more efficiently than mono-cropping. One of the biological benefits of agroforestry is that trees use portions of the biosphere to increase biomass production, which annual crops can't generate. Farmers have practiced agroforestry for thousands of years. Recently, it has developed as a science that promises farmers will help increase crop productivity and profitability (MacDicken & Vergara, 1990). In the ago-ecosystem, as the number of uncultivated land decreases, the number of native plants also decreases, which reduces the availability of pollen and nectar sources (O'Toole, 1993). Forest edges around agricultural land provide foraging, nesting, and mating sites for all bees. Forest edges provide diverse floral resources throughout bees' active periods. Also, the complex vertical structure of forest edges offers sustainable shelter for all bees and nesting sites for both cavity and ground-nesting bees. As a result, forest edges act as reservoirs of pollinators, which directly benefit crop production (Bailey et al., 2014). Even in some countries like India, Bangladesh, Sri Lanka, Thailand, and the Philippines, farmers prefer to plant or allow the growing trees like *Acacia nilotica* and *Cocos nucifera* L. in the crop fields to persist from natural regeneration (MacDicken & Vergara, 1990). In agroforestry, plant diversity reduces the risk of total crop failure from pest infestation and climatic stress, which is spread among many species. Even in the temperate region, this system includes windbreakers, riparian buffers, alley cropping, hedgerows, shelter belts, and forest farming to support pollination services (Schoeneberger et al., 2017).

The wild bee population plays an efficient role in producing many crops. Agroforestry is a good habitat option and habitat corridor for wild bees, especially solitary bees, and it supports pollination services by maintaining structural and functional diversity in the agroecosystem (Jose, 2009). Specifically, agroforestry provides nesting opportunities that significantly benefit cavity-nesting species. This system with multiple wild flowering trees offers additional resources for wild bees (Kay et al., 2019). Studies show that wild bee richness, diversity, and dispersion are higher in agroforestry than in monoculture agri-landscape, enhancing niche complementarity and effectively filling gaps in niche traits (Staton et al., 2022). This practice also acts as a pollinator buffer by reducing contact with pesticides and contaminated water (Reichenberger et al., 2007) (Fig. 1.1.).

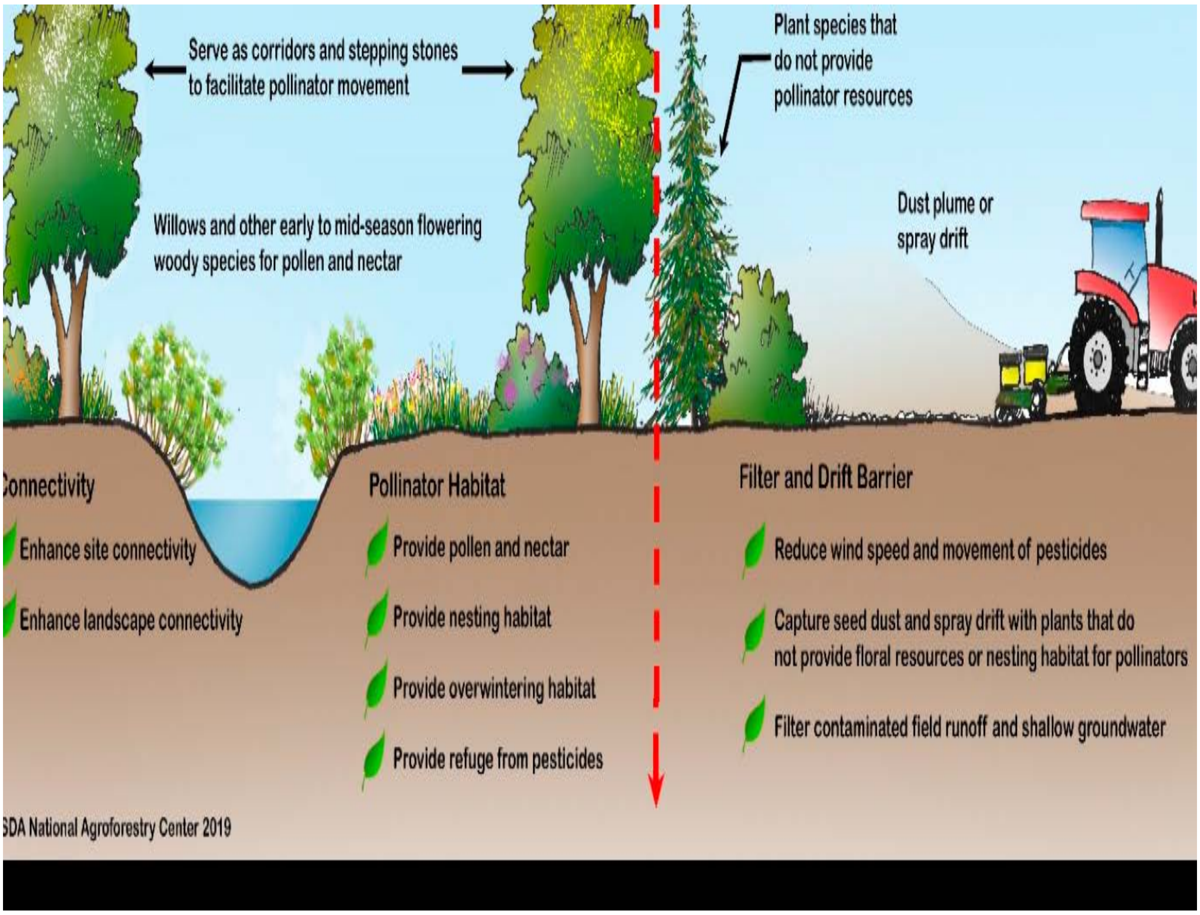


Fig. 1.1. Conceptual diagram illustrating typical functions that a generic agroforestry practice can provide to insect pollinators (Bentrup et al., 2019).

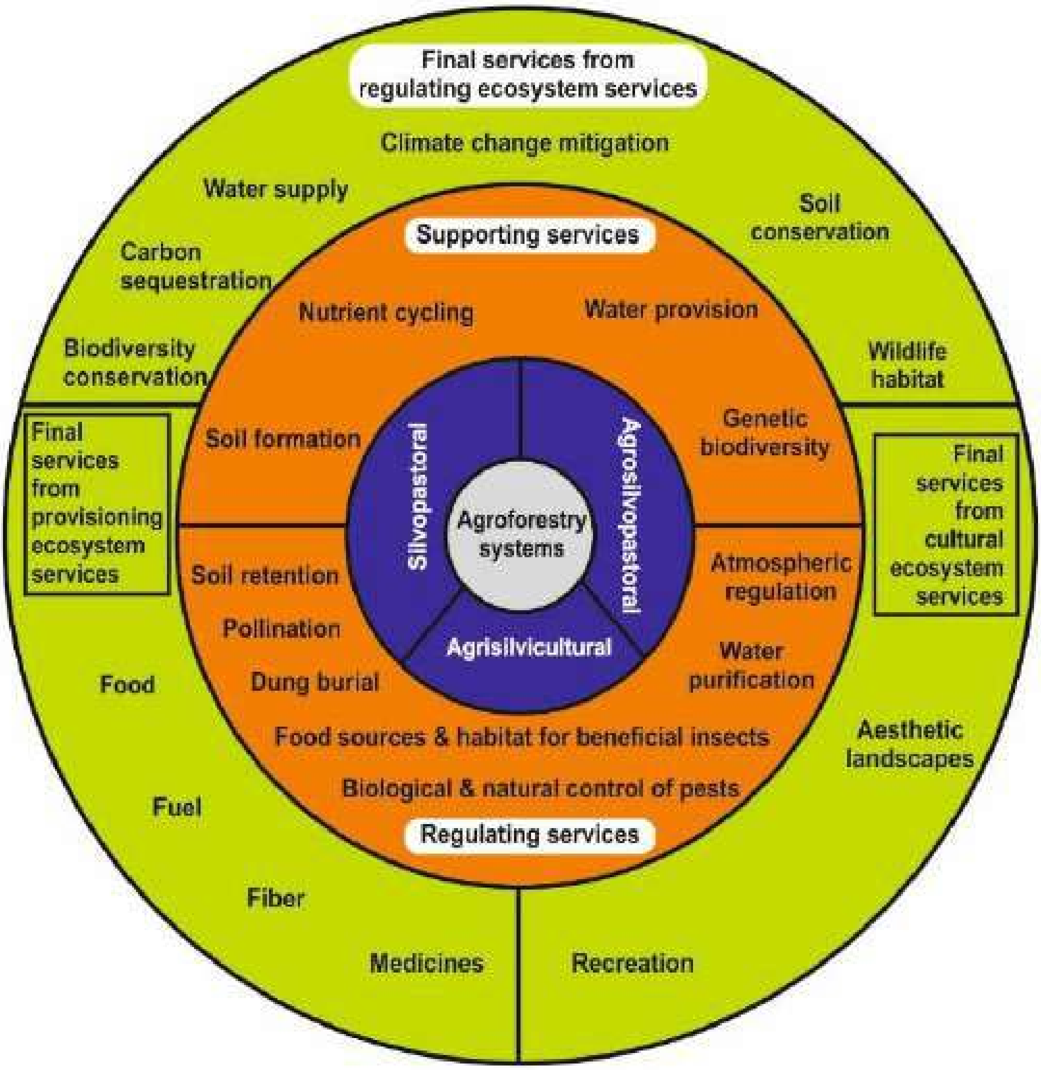


Fig. 1.2. Final ecosystem services from agroforestry systems (Millennium Ecosystem Assessment, 2003).

1.6 Pollinators threats

Habitat loss (Bommarco et al., 2014), climate change (Memmott et al., 2007; Burkle et al., 2013), alien species (Thomson, 2006), pollution, pesticides (Alston et al., 2007) and other changes in the environment threaten the species richness of both the bees and the plants from which they obtain their food, which may have far-reaching consequences for the integrity, stability and composition of the ecosystems and a global pollination crisis may threaten world food supplies. The assignment of bees for plant reproduction through pollination is beneficial. The ecosystem services of bees have been under profound observation from conservationists and farmers in recent decades due to their drastic decline. Since the 1950s, diseases, pests, and pesticide use have led to a decline of more than 50% of managed hives in Europe (Potts et al., 2010), increasing management costs because of increases dependency on native bees for pollination. IUCN's Red List assessments indicate a greater chance of extinction exists for 30% of island pollinators and 16.5% of land pollinator species.

1.6.1. Environmental threats

Climatic conditions generally control the distribution and density of species, including flowering plants and pollinators. Climate change significantly contributes to the declining bee population (Kerr et al., 2015). Different studies show bumble bees are resistant to a temperature above 30^0c (Plowright & Jay, 1966); as a consequence of climate change, the diversity and distribution of bumble bees have reduced (Martins et al., 2015; Sirois-Delisle and Kerr, 2018). Rainfall patterns change due to climate change, increasing water stress, and limiting flowers. In Australia, drought intensity increases due to reduced rainfall, which is the impact of climate change. The consequence of the scenario reduced honey sources and nectar flows (Hoffmann et al., 2019) and led to yield loss of beekeepers. Most of the pollinators are ectotherms as they are invertebrates. Kuo et al. (2023) studied the change in behavioral patterns of bees associated with the effect of elevated temperature on energy metabolism. Weather highly influences bees' foraging rates (Vicens & Bosch, 2000), which affects the flight speed, flight duration, and foraging behavior (Wratt, 1968; Heinrich & Heinrich, 1983; Corbet et al., 1993; Wood et al., 2005; Abou- Shaara, 2014).

Climate change impacts the interaction between plants and pollinators through changes in population densities, species composition, and phonological or spatial mismatches (Hegland et al., 2009). Changes in the phenology of plants, such as early budding, delayed flowering, and fruit and seed malformation, can adversely affect the pollination and productivity of the ecosystem (Thuiller et al., 2008). Due to climate change, the functional attributes of the bees (tongue length) and floral partners (tubes) are becoming mismatched and causing a significant threat to their mutualistic associations (Miller-Struttmann et al., 2015). Global warming threatens the habitats of some keystone and charismatic bee species. Insects have a limited temperature tolerance; as a result, they became the first victim of climate change (Connor, 2008). Temperature, relative humidity, and wind affect the quantity and quality of flower nectar bees attract (Somerville, 1999). Low temperature and excessive moisture have a dual effect on slowing pollen release and lowering bee activity (Joshi & Joshi, 2010).

1.6.2. Anthropogenic threats

1.6.2.1. Habitat loss and fragmentation

Changes in LULC are the dominant cause of biodiversity decline and are expected to be an ongoing threat to worldwide biodiversity (Millennium Ecosystem Assessment, 2005; Ostberg et al., 2015). Habitat loss is currently the leading cause of species endangerment. Meta-data analysis shows that habitat loss and fragmentation negatively affect species richness and abundance of wild bee species (Winfree et al., 2009). According to the IPBES report, urban-industrial development, unethical timber extraction, hydro projects, mining, unrestrained tourism, the introduction of invasive species, monoculture, and intensive farming exacerbate pollinator loss. Invasive plant species have a striking adverse effect on foraging pollination and fertilization of flowering species (Morales & Traveset, 2009). Habitat alteration and alien species invasions reduced pollinators' foraging rates (Montero-Castaño & Villa, 2012) and foraging distances between flowers in response to the volume of nectar received (Bronstein, 1995). Also, they disrupt the interaction between a plant and its pollinators. Altered landscapes, apart from bees, impact the foraging rate of vertebrate and insect pollinators.

Species restricted to fragmented areas will disappear in the short, medium, and long term, depending on the intensity of disturbance. Dispersal ability and colonization, gene flow (Allee effect), and changes in the inter-specific interactions will affect the rate of decline in the population (Araujo et al., 2004). A study in Mexico (Cairns et al., 2005) showed that fragmentation affects the abundance and diversity of stingless bees. Habitat fragmentation also affects bee population demographics and their nesting site selection. Few studies found the critical factors of bee decline -1) individual reproductive rates decrease as fewer capita offspring production or increased rates of parasitism and predation. 2) Changes in population dynamics through immigration and emigration. 3) Loss of nesting food resources 4) reduced connectivity to appropriate habitat (Tscharntke et al., 1998; Steffan-Dewenter, 2003; Palladini & Maron, 2014). Species diversity and richness decline in agroecosystems due to habitat fragmentation, which affects the ecological functioning (Lawton, 1994; Kruess & Tscharntke, 1994), as the pollination success and seed set (Corbet et al., 1991; Rathcke & Jules, 1993). Many fragmentations in habitat enhance the crowding effect in a short-term period, eventually moving towards long-term extinction risk (Ewers & Didham, 2006). However, a productive land-use management design can give a perception for future conservation and management planning for habitat improvement and regulate further deterioration (Chauhan et al., 2021).

1.6.2.2. Uses of inorganic pesticide

India is one of the most developed agricultural countries in the world. At present, the application of pesticides is a widespread practice. However, pesticides may directly and indirectly affect species diversity and composition in the agricultural landscape, including beneficial insects like pollinators, especially bees. Also, habitat alteration, habitat degradation, habitat fragmentation, the introduction of alien species, GMO crops, and agrochemicals are the major threats to decreasing bee populations (Bond, 1994). In recent times the decline of pollinators and their impact on agricultural production has been severe (Bhattacharya & Basu, 2018). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2016) states in its assessment report on pollinators that pollination and food production have acknowledged the importance of incorporating the expertise of existing indigenous and local knowledge systems in conserving and managing diverse pollinators, including bees.

Pesticides, i.e., synthetic chemicals, are highly responsible for pollinator mortality (Kearns & Inouye, 1997). Integrated Pest Management (IPM) is a broad approach to keep pest populations under the economic injury level. Chemical control is still the most approachable method in pest management in India. Despite knowing the harmful effects of pesticides, their use has increased by 2,00,000 Tons by 2,000 A.D. (Shukla & Upadhaya, 2010). The term pesticide covers multiple compounds, including insecticides, herbicides, fungicides, rodenticides, molluscicides, nematicides, plant growth regulators, and others. Active and inert ingredients compose pesticides. The active ones damage the pest; inert ingredients are solvents in the solution (inert ingredients are not necessarily non-toxic) (Wasim, 2009).

Pesticides may directly and indirectly affect species diversity and species composition in the agricultural landscape. In this landscape, both natural and semi-natural landscapes support a huge insect diversity, from pollinators to predatory insects, which provide services in semi-natural and cultivated areas (Crist & Peters, 2014). Environmental stress positively correlates with inbreeding depression in any population (Fox & Read, 2010). The adverse effect of pesticides is magnified in humans, causing various carcinogenic effects.

The absence of pollinators can hamper the plant mating system heterozygosity and increase various deleterious traits associated with breeding (Kearns & Inouye, 1997). Wild pollinators have decreased in occurrence and diversity in many places in Europe and America. Pollinators are declining at an alarming rate but are a crucial factor in agriculture; hence, pollinator habitats and diversity need maintenance in an agricultural landscape. This conservation is essential to maintain food production and ensure food quality. Habitat loss and intensification of agricultural practices threatened wild and domestic pollinators. A study in Uttarakhand observed higher species richness of primary pollinators in inorganic farming than non-organic agriculture (Mehrwar, 2022). Organic farming, intercropping, and crop rotation practices, along with planting flowering strips and maintaining wild native flower vegetation, can enhance the foraging rate of bees. Since most bees prefer to forage in the morning and afternoon, applying pesticides after the afternoon and not in the morning allows a longer interval between bee forage and spraying. Proper strategy and policy need to be implemented with the help of indigenous and local knowledge to reduce the risks associated with pollinator decline in any part of the world.

1.7 Conservation

In 1993, the Pollinator Monitoring Program incorporated pollinators, established and recognized by the signing of 168 countries. Pollinator monitoring is an essential goal for collecting data from several countries. The best data for bee communities from the EU show strong evidence of decline. Throughout European countries, around 65% of bee species were listed as conservation concern (Mohra et al., 2004; Fitzpatrick et al., 2009). The Convention of Biodiversity implemented numerous significant steps to conserve pollinators worldwide under the implementation of Decision III/11, "Sustainable use of agricultural biodiversity." To prevent the pollinator population's decline, the International Pollinators Initiative was established. The UN designated 20th May World Bees Day to inform people of their significant roles in sustainable development and the threats they face.

Pollinator abundance will be affected more severely in the long-term scenario will affect pollinator abundance more severely. Natural forests are a suitable habitat for wild bees, but due to extensive deforestation, they are under threat. Agroforestry provides niche diversity and reduces pest problems (Stamps & Linit, 1997). Bees establish a compelling association between agriculture, forestry, biodiversity, food security, nutrition, and sustainable development. The government needs to implement a necessary policy to expand facilities to educate small- and large-scale farmers about the environmental implications of agrochemicals; it is also essential to promote the scientific and rational use of different agrochemicals. Also, educating farmers about using bio-fertilizers and organic pesticides and how to restore soil health is necessary.

1.8 Gaps and limitation

The entomo fauna pollinators are pretty diverse, but their conservation effectiveness could be more robust due to inadequate taxonomic knowledge, evolution, morphometry-based studies, and a lack of distribution patterns. As the entomo pollinators are declining faster, we must incorporate their declining population into the IUCN red list. The entomofauna need protection at a regional level through the execution of pollinator-based conservation programs. Butterflies, moths, beetles, and odonates are the most studied groups in the entomofauna. Bees are the major pollination contributor, but we ignore wild and native bees for study.

The striking gaps in bee conservation are a great need for monitoring of bee populations to provide information about long-term population trends. Such monitoring would highlight significant gaps in the status and trends of pollinators and their pollination through citizen science projects, especially for wild bees. We also need to study how land use effects different bee species diversity and population. This information can help conservation planners prioritize the conservation of sensitive species. Earlier studies from tropical and temperate systems show that land conversation can dramatically change species composition (Winfree et al., 2007; Brosi et al., 2007; Cane et al., 2006). Researchers still need to study even life table analysis or population viability analysis (PVA) of bee species. Solitary bees have low fecundity rates for insects, but adult females have 2- 30 offspring per lifetime, which means the survivorship of juveniles is much higher (Winfree et al., 2010). PVA can determine the population sizes of bee species persistence and land area required for reserves. We need to know the limiting factor of the bee population so we can use it in the restoration of nesting sites or floral resources. Also, we need more studies on climate change's effect on bee species.

Pollinator population declines are one type of global change that can impact the layout and structure of terrestrial ecosystems. Management of ecosystems based on knowledge pollination is vital for managing individual species and ecosystems. A lack of knowledge about the pollination ecology of bees and plants may lead to detrimental management measures. The challenge in using pollinators for crop pollination is for crop quantity, and management techniques exist only for a small number of non-

Apis bees. Also, we need a good study about pollination in agroforestry, which includes the best plant combination to provide foraging resources in space and time, distance to target crop and orientation (Bentrup et al., 2019), to protect pollinator species and their habitat, as agroforestry has a role to play in ameliorate modern farming and mitigation of the ongoing loss of the wild bees, which intensely driven by prevailing agricultural practices.

Chapter - 2

Literatures Review

2.1. Role of bees as pollinators in forest ecosystem

More resources (food and nesting) for bees were promoted by landscapes with a higher proportion of forest area and environmental heterogeneity, supporting their diversity in the forest (Nery et al., 2018). It could be challenging for some sensitive bees to forage outside of forest patches for feeding due to different climatic conditions (drier and hotter than understory) (Hilario et al., 2001; Baudena et al., 2015); for them continuous and higher amount of forest in the landscape was required to lower the isolation (Fahrig, 2003), leading to more efficient foraging by reducing the distance and time needed to access open areas (Jha & Vandermeer, 2010).

Less diverse bee communities were presented in forest areas than in open areas (Nery et al., 2018). A similar study in Nigerian forests showed that the abundance of honey bees was higher than that of wild bees (Garba et al., 2023). According to Eckerter et al. (2022), The abundance of wild bees was positively correlated with canopy openness, and diversity was increased with landscape heterogeneity. Light penetration was hindered by mature forest characteristics with a closed canopy. As a result, the growth and blooming of shrubs (understory of the forest) were prevented (Terborgh, 1985). The values of species richness in bee communities in early and intermediate stages were contradictory; intermediate stages were composed of common and dominant species, whereas in mature stages, diversity and richness were substantially lower (Zitomer et al., 2023). Usually, the foraging bees on flowers in the understory of forest areas were surveyed by researchers, revealing low species diversity. Sampling only on this stratum might not correctly assess bee communities in forest patches. During the flowering season, most of the flowers bloom in the canopy in mature forests, and it was expected bees would be drawn there to visit the flowers (Ramalho, 2004). This limitation could be overcome with novel methods to sample bees foraging flowers in the canopy, but a wide range of trees needs to be developed. However, the results of bee communities in and outside forest patches were found to have ecological significance and management value at the landscape level.

The forest was considered a high-quality nesting site and an essential source environment for bees (Brosi et al., 2008; Tscharntke et al., 2012; Ferreira et al., 2015), so nesting in the forest was preferred by bees. Entirely reliance on forest areas was shown by ground-nesting bees, making them most susceptible to forest loss (Ferreira et al., 2015). Environment heterogeneity was associated with high bee species turnover, which enhances specialization and niche differentiation of species (Eckerter et al., 2022). Sustainable Actions must be taken to conserve beneficial rare species while preserving forest areas. Due to increasing rates of land use change in primary forests worldwide, secondary forests were becoming alternative food sources throughout the year for pollinators, especially for bee fauna (Armas et al., 2020).

2.2. Population of pollinator insect and their role in agro forestry ecosystem

Nowadays, agroforestry is recognized as a significant ecosystem, especially in tropical countries, and is also becoming an intensive land management system. It is constituted by agriculture systems and is considered to have potential as biodiversity conservation sites. Rural livelihood is provided by the agroforestry ecosystem alongside biodiversity conservation in a sustainable land use system. The transition from conventional agricultural to agroecological agricultural practices is made by this system. A richer insect diversity was provided by combining crops and diverse plant species in the forests due to increased niche diversity compared to agroecosystems (Stamps & Linit, 1998). A better niche diversity for arthropod fauna in both time and space was offered by the combination of crops and wild plants than a polyculture or monoculture of annual crops (Stamps, 1998). It had been revealed by several studies that a significantly diverse arthropod community was supported by trees, due to their structural complexity, than shrubs or herbaceous annuals and perennials (van Emden & Williams, 1974; Lawton & Shroder, 1977; Strong & Levin, 1979; Niemala et al., 1982). The "species-energy" theory, the relationship between biomass and species diversity, had been suggested as an extension of the species-area theory (Wright, 1983), and a positive correlation had been found between biomass and species diversity (Pimentel et al., 1992). Therefore, insect diversity was increased in the agroforestry ecosystem over annual crop polycultures or monocultures based solely on available vegetation area or biomass. Also, traditional crop management provides a limited time frame for particular insects, whereas trees offer predictable resources and constant niche availability (Southwood, 1978; Stamps, 1998). A continuous nutritional source for the insects and a diverse microclimate for their habitat were provided by a combination of both trees and crops. More diversity and abundance of natural enemy insects were enhanced by agroforestry practices than traditional alley cropping systems (Peng et al., 1993).

The positive interaction between trees and crops was maximized, and the negative interaction was minimized as resources that the crops do not use are used by trees (Varah, 2013) in this ecosystem. A crucial role in sustaining pollinator diversity was played by a heterogeneous agroforestry ecosystem (Klein, 2003; Perfecto, 1996) by providing extended floral resources for pollinators (Sinu & Shivanna, 2007) and nesting sites, like Xyclopid bees region nest in rotten wood (Aluri and Roa, 2006) which were widespread in forest and agriculture landscape. Similarly, natural forest was needed by wild bees to continue foraging on wildflowers (Carvell et al., 2017). An essential role in wild, native plants and crop pollination was played by wild bees and honey bees; in fact, for some crops, they were more critical and effective pollinators than honey bees (Kevan et al., 1990). Agricultural fauna, biodiversity, and ecosystem services were supported by this practice (Staton et al., 2022). Increased pollinator species richness and abundance have been observed in more intensive agriculture (Connor, Courtney & Yoder, 2000; Debinski & Holt, 2000). Accumulation of pollinator species can be increased positively with floral resources, i.e., nectar resources increase at the community level (Potts et al., 2003). Agroecosystem, a close to the high proportion of natural habitat, benefits from bee abundance and diversity, especially wild bees, foraging movement, and mutualistic behavior (Klein et al., 2006; Hagen & Kraemer, 2010; Balachandran et al., 2017). The unique contribution of rarer species to the ecosystem was still more vital than that of common species (Staton et al., 2022).

A significant contribution to the fruit set of coffee by species-rich solitary bee species had been reported by Klein et al. (2003), and their diversity in the coffee field correlated with light intensity and species number of plants. In contrast, the diversity of social bees was observed to decrease with the distance of the forest. The dependence on plant-pollinator interaction was influenced by temporal, spatial scale, and environmental changes, studied by Burkle and Irwin (2009). The primary weather variables were affected by agroforestry practices, which reduced wind movement and modified temperature in the agricultural landscape (Bentrup et al., 2021). Additionally, closely connected nesting and foraging sites in agroforestry landscapes were beneficial for wild bees, as Kay et al. (2019) found. Multiple resources for wild bees to fulfill their forging and nesting requirements were accommodated by the agroforestry ecosystem. Also, a role in maintaining the genetic diversity of native plants along with honey bees was played by native bee communities (Jha & Dick, 2010) like bumble bees due to their "buzz pollination," plays a crucial role in crop pollination as well as generalist pollinators of native flowering plants (Buchmann, 1983; Memmott et al., 2004). The consequence of eliminating all agroforestry trees would be a trend towards reducing pollination services. It was found by Chatterjee et al. (2020) that restoring the cover of natural vegetation around agroecosystems above the minimum threshold level could be the following strategy for conserving pollinators and enhancing pollinator-dependent crop yield.

2.3. Role of bees as a pollinator in agroecosystem

In agriculture land, bees were considered the essential pollinators for pollination and crop production. Over 90% of the leading global crops were pollinated by bees pollinated (Potts et al., 2016). Non-Apis species were acknowledged as more effective pollinators than honey bees (Javorek et al., 2002; Kreman et al., 2002), and they can enhance crop production (Greenleaf & Kreman et al., 2007). Almost 15% of crops were pollinated by domestic bees, while around 80% are pollinated by wild bees (Goswami & Khan, 2014). The unavailability of bees leading to no cross-pollination causes a reduction in seed size, number, viability as well as yield (Delaplane et al., 2000); even single bee species visited did not yield heavier fruit seeds compared to the flower visited by different bee species (Barbosa et al., 2019). Bee species of the family Apidae were most abundant as they can explore diverse environments and intensive agriculture (Ferreira et al., 2015). Widhiono et al. (2022) observed that the diversity of wild bees was not affected after introducing honey bees to the study sites. Still, a decrease in their abundance was observed at the end of the flowering period, which means managed colonies reduce the potency of wild bee pollination if introduced in the early and mid-stage flowering period.

Bees were attracted to crops of the family Brassicaceae, an excellent source of nectar and pollen (Masierowska, 2003). A pollinator was needed for *Brassica juncea* to transfer pollen from male flowers to female flowers as it is a self-incompatible crop (Roy et al., 2014). Sunflower is one of the essential vegetable oils cultivated in West Bengal. 45% of the world's total production was shared by sunflowers, which have a high demand for their health appeal. A significant role in sunflower seed production was played by different honey bee species (Said et al., 2015). Sunflowers were visited by bee species to fulfill their needs for their colony and passively contribute to their role in pollination (Basak and Mandal, 2018). Higher quantities of nectar and sugar in sunflowers attracted more wild bees and honey bees for pollination service, enhancing the productivity of oilseeds (Mallinger & Prasifka, 2016), among which *Apis* bees were the dominant (Vishwakarma & Ghatak, 2014). It was also observed by them that in West Bengal, March was the peak period for the foraging of bees, especially in the morning in sunflower cropland. The hybrids were preferred by honey bees to the old population of sunflowers, as indicated by another study, but hybrids produce less nectar, consequently, the probability of honey production was low (Rinku & Chaudhary, 2017). Sesame was visited by a diverse group of bees for pollen and nectar (Selvakumari et al., 2022). Oil seed production could be increased by up to 22% -33% through bee and open pollination (Panda et al., 1988). Edible oil was sourced vibrantly from sesame seed and ranked third in India. Sesame crops were more actively visited by *Apis* bees than non-Apis bees (Selvakumari et al., 2023).

Pigeon pea (*Cajanus cajan*) flowers, with bright corollae and nectar and pollen production, attracted bees for pollination. A more significant seed yield was observed by bee pollination than self-pollination in a Verma et al. (2018) study in Faizabad, India. Carpenter, social, and solitary bees were the most abundant in pigeon peas (Otieno et al., 2014). Outcrossing of this flower was facilitated by *Xylocopa* and *Megachile* bees, as they can press on the keel of the flowers to open and access the pollen and nectar (Martins, 2008; Pando et al., 2011; Pando et al., 2018).

Essential pollination for monoecious plants like Cucumber (*Cucumis sativus*) was provided by bees, honey bees were considered crucial pollinators for cucumber, but studies showed that more effective pollination and yielded more fruit sets were achieved by stingless bees and honey bees (Amano, 2005; Rai et al., 2008; Nicodemo et al., 2013; Azmi et al., 2017, Hanif et al., 2022). Cucumbers pollinated by stingless bees were observed to be heavier, longer, and broader in dried seed weight than treatments without stingless bee pollination (Azmi et al., 2017). For successful pollination, around twenty bee foragers were needed for most cucurbit female flowers (Inam et al., 2015). In eggplant, the foraging rate of bees is more extensive than in other crops (Sree et al., 2018). Solanaceous (eggplant, tomato) and Cucurbitaceous (ridge gourd) crops were effectively pollinated by buzz pollinators (Kumar & Rai, 2020). Eggplant flowers had abundant pollen, but the expulsion of pollen requires vibration by insects like "buzz pollination." Wild bees were more efficient in buzz pollination than honey bees (Buchmann, 1983; Herren & Ochieng, 2008). Honey bees were observed to forage eggplant flowers to scrape the pollen and spread over it after foraging by buzzing bees; due to a lack of the ability buzz pollinate, they are also considered poor pollinators for eggplant (King & Buchmann, 2003; Udayakumar et al., 2021). In an earlier study by Herren & Ochieng (2008), it was observed that *Xylocopa caffra* was an effective pollinator for eggplant crops. Its visitation rates were significantly reduced with distance from the wild habitat, as the flower of wild plants is a vital foraging source for bees. Even in tomato (Solanaceous) cultivation, better performance as pollinators was observed in wild bees than honey bees (Garibaldi et al., 2013; Francisco et al., 2022) as sonicating bees could efficiently extract pollen from poricidal anthers (Greenleaf & Kremen, 2006) and increased yield of the crop (Cooley & Vallejo-Marin, 2021), but adverse effects on the pollinator community were caused by exotic bee fauna, due to compete with native fauna (Dafni et al., 2010). The seed yield of hermaphroditic crops like tomatoes was significantly increased by bees. In another study by Barbosa et al. (2019), the existence of non-sonicating bees was observed due to the low presence of sonicating bees in the tomato field. Observations by Kumar & Rai (2020) and Gautam

& Kumar (2018) showed that the population of *Apis dorsata* was dominant in ridge gourd crops in Bihar, India.

2.4. Influence of meteorological parameters on foraging activity of bees

Meteorological parameters like temperature, wind speed, and rainfall were significantly related to bee abundance and foraging activity (Bhattacharyya and Chakraborty, 2016). The foraging pattern of bees was affected by the negative influence of relative humidity, rainfall, and minimum temperature, as unveiled by the correlation coefficient between weather parameters and pollinator foragers. In contrast, the foraging pattern and bee population were positively impacted by maximum temperature and mean evaporation (Dorjay et al., 2017). The secretion of nectar increases with high temperatures in the afternoon, and high abundance was observed in the afternoon in earlier studies on sunflowers (Ali et al., 2015). The same trend was recorded: bees were abundant in the afternoon compared to the morning, and *Apis dorsata* was the dominant visitor in the mustard field (Shakeel et al., 2019). Similar results were shown in a Sunflower study, where contrasting environmental interactions impact nectar volume, concentration, and sugar composition. The rate of bee visitors was positively correlated with nectar quantity, and the most significant interaction of visitors was observed for nectar volume, with more nectar being produced under warm conditions (28^0C); in another set of experiments, maximum nectar was produced under a mild (21^0C) temperature when consistent humidity (65%) was present, which indicate the influence of moisture of nectar production (Prasifka et al., 2023).

As per Abbasi et al. (2023), it was observed that more pollen was carried by *Apis* bees in the early morning, around 10 a.m., from the cucumber farmland, and pollen collection gradually decreased after the afternoon (12 p.m.), foraging of bees varied across three hours of the day. Honey bees were observed to forage mostly in cucumber agriculture fields from April to May, and foraging activity decreased during monsoon. Foraging activity and pollen collection of bees were reduced by bad weather, higher wind speed, and rainy season. It was observed that bee activity was affected by temperature, wind, and relative humidity (Mahfouz et al., 2012). Early morning foraging activity was preferred by Giant black bees, mainly due to their difficulties with dehydration and thermal regulation at high temperatures (Pereboom & Biesmeijer, 2003). Previous studies in eggplants confirm that the peak period of stigma receptivity and pollen germination was optimum between 8.00 and 11.00 h. (Srinivas et al., 2016; Das et al., 2017; Ginoya et al., 2021; Paschapur et al., 2022), simultaneously during this period, the highest activity of bee foragers was observed, and this combination resulted in optimum pollination in eggplant (Nunes-Silva et al., 2013; Udayakumara et al., 2021).

2.5. Influential factors of pollen transport network

On average, seven pollen species were received by most plants, and their pollen was donated to five species; much pollen from many species was received by very few plant species. More hetero-specific pollen was received by generalized plants than by specialized plants (Fang et al., 2013). Most flowering plant species were pollinated by more than one animal species, and more than one plant species was often visited by most pollinators. As a result, a high diversity of pollinators was provided by a high diversity of plants, especially bees, identified as the primary pollinators and one of the key elements responsible for maintaining plant diversity (Michener, 2007). The plant's phenology means that some pollinators were more frequent visitors and pollinators than others. For bees, the essential source of protein was provided by pollen, which was also necessary for their offspring, and nectar acts as the source of energy for adults of both sexes. In reality, a type of facultative mutualism was represented by the mutual independence of bees and plants.

According to Smith (2011), an essential pollinator resource was represented by flowering cover crops, which positively affect the agroecosystem. Even non beneficial weed populations were reduced by cover crops by modifying abiotic factors to create conditions suitable for weed growth. As a result, there would be a decrease in the use of weedicides. Furthermore, the enhancement of food sources and habitats for pollinators like wild bees and other insects in natural areas surrounding the agricultural fields could be achieved by plant diversity (Nicholls and Altieri, 2012). Various studies (Mackenzie and Winston, 1984; Kremen et al., 2004; Morandin, 2007) have shown a positive correlation between the population and diversity of native bees and the wild floral diversity surrounding the farmlands. The conventional farmlands isolated from wild vegetation were observed to experience insufficient pollination services from native bees due to the reduction of diversity and abundance of native bees. Flowering plants and weeds surrounding and within the farmlands provided alternative forage options for pollinators. Hence, proper management was required to enhance pollinator's diversity and abundance (Nicholls and Altieri, 2012). Not only could sometimes non-crop plants be utilized for habitat restoration, but their association with pollinators, natural enemies, and pests builds a multi-functional component (Laha et al., 2022), as a heterogeneous landscape with diverse communities exhibits complex plant-pollinator interactions (Moreira et al., 2015).

An essential role within plant-pollinator webs was played by honey bees and wild bees; these mutualistic webs benefited both partners. The keystone species of this interaction system was bees (Bond, 1994; Kratochwil, 2003), and the loss of the species always cost serious consequences, especially for the wild plants (Tepedino, 1979; Wcislo & Cane, 1996; Biesmeijer et al., 2006). It was assumed by experts that pollen grains were likely to be transferred off their bodies of bees (apart from scopae) to stigma, and pollen grains carried by scopae were utilized to feed their larvae and not for pollination (Thorp, 200; Alarcon, 2010; Stavert et al., 2016). A nominal portion of pollen (3.7%) was deposited onto the stigmas of flowers by bees, and the rest was used to feed their larvae. According to the Anthecologist, the portion of pollen that a bee removes from an anther and deposits to a stigma is known as "pollination efficiency" (Castellanos et al., 2003; Schlindwein et al., 2005; Koski et al., 2018; Danforth et al. 2019). Lower pollen-transfer efficiency was observed in oligolectic bee species compared to polylectic species foraging on the same host plant due to the large amount of pollen they sequester (Parker et al., 2016). The first empirical evidence demonstrated that the pollen efficiency of generalist bees could differ based on the plants from which pollen was collected. The pollen on bees' bodies mainly differed in morphospecies composition from the pollen carried by scopae (Weinman et al., 2023). A major role in maintaining the plant-pollinator network was found to be played by the bees of the Apidae family in a study conducted in Brazil (Kleinert & Giannini, 2012). In an agroecosystem, effective pollination for crop plants was provided by native bees, which were diverse and abundant near the natural ecosystems (Kremen et al., 2004; Ricketts et al., 2008; Udaykumar et al., 2021).

Plant-pollinator interactions were dynamics in space and time; they differed by sub-seasons, across habitats, and species turnover (Hervias-Parejo et al., 2023). A study in the Garhwal region of India observed plants like *Ageratum conyzoides* and *Tagetes erecta* bloom throughout the year and became continuous food sources for bees (Gloch et al., 2023). Even bee visitors foraging at different times of the day might be ensured that floral visitation coincides with pollen availability and stigma receptivity, which could vary throughout the day (Kaul, 1991) and even in season. Influenced and reshaped plant-pollinator interactions were brought by habitat alteration, other anthropogenic disturbances, and species richness and abundance (CaraDonna et al., 2017; Chacoff et al., 2018). Brazil documented the adverse effect of the array of plants in an urban environment, disrupting plant-pollinator network reported in a case study (Zotarelli, 2014). Even the decline of a keystone plant like *Cirsium pitcher* perturbed plant-pollinator interaction due to habitat loss indirectly affect the pollinator diversity. The short-term adverse consequences on the plant-pollinator network structure could be directly related to the long-term effects on the durability of any community (Sandacz, 2023). It was reported by Carmo et al. (2023) that plant-pollinator dynamics were negatively impacted by invasive grass and non-native honeybees; if phenotypically similar, they served as magnet species for pollinators and resulted in reduced foraging rates in neighboring native flora. The number of bee visitors was negatively influenced by presence of invasive grass through the alteration of community structure. The richness of native bees and their foraging rate was decreased by the introduction of non-native honey bees, consequently leading to a reduction in plant reproductive success (Rymer et al., 2005). The joint influence on plant-pollinator interaction was exerted by neutral and niche-based processes; by focusing on this aspect, rare bees can be conserved by conserving interactions between plants, and rare bees could save rare bees. Incorporating niche-based differences in conservation strategies through the restoration and preservation of natural habitats with a high abundance of zygomorphic and actinomorphic flowers appears to be the most recommended strategy for conserving wild bees (Sydenham et al., 2022). Along with that, nutritional diversity should be considered for habitat restoration, as plant genera and bee subgenera are grouped by pollen macronutrient value, expressing potential nutritional niches (Vaudo et al., 2024).

2.6. Role of Bees in Ecosystem Services

The concept of Ecosystem service (E.S.) encompasses any positive benefits that wildlife or ecosystems provide to human beings. Ecosystem services could be categorized into four categories; crop pollination comprises subcategories of supporting categories (Millenium Ecosystem Assessment, 2003). Crop production was enhanced by ecological intensification through the support and regulation of ecosystem services management in agriculture practices (Bommarco et al., 2014). The availability of information that promotes both conceptual and instrumental discussions about natural resource management was required for the combination of E.S. in decision-making and landscape-level planning (Wright et al., 2017). It had been noted that most of the essential cash crops (coffee, cocoa, almond, etc.) of the world benefited from pollinators in terms of yields and quality and provide employment and income for millions of people (Potts et al., 2016). The economic value of agricultural products through pollination services was estimated to be 153 billion Euros annually globally in 2005 (Gallai, 2009).

According to the study by Koh et al. (2018), the increase in almond production was caused by the high foraging density of *Osmia lignaria*. However, E.S. at that site was already provided by honey bees. Even for several important crops like blueberry, wild native bees were more efficient and effective pollinators than honeybees (Cane, 1997). Habitats like ground nesting sites, bark nesting sites, and branch nesting sites for wild and native bees would be provided by forest areas near agriculture fields, enhancing bee diversity, as result increases their E.S. in-surrounding. In China, the pollination service of bees in Litchi and Longan orchards was significantly impacted due to land use changes in natural and semi-natural habitats like- forest land, rainfed cropland, and grassland from 2015 to 2019 (Ke et al., 2022).

Also, the decline in pollinator population was noted to cause a deficiency of nutritional value in the human diet, as major proportions of micronutrients, vitamins, and minerals in the human diet were supplied by pollinator-dependent fruits, vegetables, nuts, and oil crops supply (Potts et al., 2016). When the pollinator population was in decline, there was an increase in vitamin A deficiency (Ellis, Myers, Ricketts; 2015) because vitamin A was mainly received by most people from pollinators' dependent fruits and vegetables. Crop pollination by bees was recognized as a valuable ecosystem service in many mixed agricultural landscapes and natural habitats (Allen-Wardell et al., 1998). Crop flowers visiting pollinator in different crops, the communities of pollinators visiting crop flowers were found to vary; a preference for a specific group of crops was exhibited by some bee species, and understanding the role of bee species in crop production and taking appropriate action for their conservation (Garratt et al., 2014).

The composition of the bee community was significantly determined by nesting sites, as a variety of nesting habits were exhibited by bees. Nest selection was also dependent on the bees' foraging range from resources. Bee population composition and dynamics were affected by the alternation of nesting and resource sites. The support to pollinator populations could be enhanced through landscape habitat diversity and depending on land use (e.g., agriculture, forestry, gazing lands, etc.) through intercropping, crop rotations with flowering crops, agroforestry, and creating, maintaining, and restoring of wild and native flowering plants (Potts, 2016). The correlation between the ecosystem service of bees and their natural habitat could be utilized for conservation and restoration (Kremen et al., 2007). Implementing bees' foraging behavior in any E.S. model was considered a valuable component for the spatial representation of the service, which could be validated by available field data (Fernandes et al., 2020). People's perceptions of their environment and the E.S. of pollination also needed to be understood. According to the understanding, policies and strategies to increase awareness of the importance of sustainable actions and conserve the E.S. of pollinators could be endorsed (de Oliveira and Berkes, 2014); however accurately we tried to estimate the value of pollination on services, this value continuous to failed in representing the complex set of the importance of pollinators and describe the full benefit of their ecosystem functions.

Chapter -3
Study Area
Research Questions and Methodology

The studied area, Kangsabati South Forest Division (KSFD) in Purulia in West Bengal, is characterized by undulating topography with hilly terrain in the western and southern parts, which are continuations of the Chotanagpur Plateau, one of the oldest landmasses on the earth. The studied site is the continuous forest range of Chandil Dalma Elephant Reserve, which is the northern part of Chandil Dalma Elephant Reserve. This area is dominated by sacred groves, where native flora and fauna are naturally preserved in traditional rules and beliefs. This area also has biogeographical significance and uniqueness, as this plateau formed a link between Satpura Hills and Eastern Himalaya in the past, which allowed species exchanges between these ranges (Hora, 1949). Imam et al. (2016) observed a high percentage of ground-dwelling insect diversity in Purulia. Nayar (1996) recognized Chotanagpur as one of the critical 'microcenters' for endemic flora.

A mixed cropping system is practiced dominantly in the studied area. Despite such unique diversity and agricultural dominance, it faces anthropogenic threats like deforestation, habit fragmentation, urbanization, forest fire, industries, mining industries, etc. Excess use of inorganic pesticides, herbicides, and fertilizers is becoming a threat to agro-biodiversity. All these activities have declined the bee population, and as a result, the diversity of native flora and crop production is also in danger. On the contrary, the diversity and threats to the bee population from the study area are hitherto unknown. Being one of the oldest landmasses on earth, the region might hide some unforeseen knowledge concerning bee diversity and biodiversity evolution.

3.1 Purulia District

Purulia was carved out of the former Manbhum district of Bihar and merged with the State of West Bengal in November 1956. The District occupies the 5th position in the state regarding its size. In the western part of the District of West Bengal, Purulia is surrounded on three sides by the State of Jharkhand, on the north by Hazaribagh and Dhanbad, and the west by Ranchi. On the eastern side, the District of West Bengal, i.e., Bankura, Burdwan, and on the south by Midnapore, covers the flank.

3.2. Geology

This area is characterized by undulating topography with hilly terrain in the western and southern parts, which are continuations of the Chotanagpur Plateau. The area consists of undulating plains with isolated mounds and hills, low valleys here and there mixed alternatively with long stretches of flattish area, where most of the cultivable lands of the District are located. Due to undulated topography, nearly 50% of the rainfall flows away as runoff. The area is covered primarily by residual soil formed by bedrock weathering.

3.2.1. Rock

Crystalline rocks occupy the area, a series of ancient slates with associated volcanic rocks belonging to the Dharwar systems from the southern belt. Most of the crystalline rocks are intrusive porphyritic granite gneiss, known as dome-gneiss. The dome-gneiss is a coarse granite rock composed of quartz, muscovite mica, and orthoclase feldspar, which occur both in the general matrix and as large porphyritic crystals that give a conglomeratic appearance. The color of feldspar is usually pink or grey and sometimes brick red. Numerous igneous instructions were also observed, varying in composition from high silicones to comparatively poor in Silica but rich in lime, iron, and magnesium. A peculiar siliceous and sometimes ferruginous rock also has a wide distribution. These rocks accompany the lines of faulting. A remarkable vein of blue Kyanite (Silicate of alumina) and muscovite mica (Silicate of alumina and Potash) with an average width of 60 centimeters has been found to occur in the east and western parts. Laterite also occurs in thinner layers that are relatively well distributed over the area. A few varieties can be distinguished into- a) Pisolitic in the form of loose gravel or compact, b) Conglomeratic containing both round and angular fragments of quartz, c) Conglomerate passing into coarse grit, d) Concretionary, e) Compact occurring in stratified bed. Thick clay deposits have been found in many places; in some places, the deposits attain a thickness of 20 meters. The soil is an infertile laterite of no great depth. The flat spaces between ridges require higher protection for retention of the soil that has been washed down from the higher slopes.

3.2.2. Soil

The soils are primarily passive in nature. Colluvial soil is found only in the valley bottom. Soils of undulated uplands are shallow, gravelly, and coarse, having low water holding capacity. These lands are either severely eroded or very susceptible to erosion.

The soils are primarily sedentary, formed by the weathering of the archean granite, gneiss, and schists, and are of residual type. Collucial soils are found in the valley bottom. Soils of undulating uplands are shallow, gravelly, course-textured, and well-drained with low water holding capacity. These lands are either severely eroded or very susceptible to erosion. As root penetration is hindered, quartz, feldspar, and iron concentrations are found through the depth.

Very gently sloping to moderately sloping medium land is situated between ridges, and the valley bottom soil is relatively deep, light to medium textured, and low in organic content. Water holding capacity is also low. The infiltration and permeability are generally high. Clay content increases along with depth. These lands are suitable for cultivation.

Low or valley-bottom soils are mostly colluvial. Soils are deep to very deep with medium to fine texture. Permeability is low, and it suffers drainage problems. Clay content decreases along with depth. It is formed mainly by the material brought down from high-lying areas by rains. These lands are intensively used for paddy cultivation.

3.3. Climate

The climate is hot and dry, with three distinct seasons: summer, monsoon, and winter. The monsoon starts in mid-June and lasts till the end of September. The summer is harsh and lasts from the middle of March to the middle of June. The winter lasts from December to February.

3.3.1. Temperature

The temperature tends to go down and reaches its lowest in January. The maximum temperature is highest in May, and from June, it tends to go down; it is also observed that the temperature fluctuation is negligible from July to October. Purulia is a well-known draught-prone District within the semi-arid region of West Bengal. It is characterized by high evaporation and low precipitation; the District has a sub-tropical climate.

3.3.2. Rainfall

Rainfall in the District is erratic, with occasional draughts in between rains. In some cases, rain starts late, i.e., in the latter part of July, and sometimes rainfall ceases earlier, i.e., in the last part of August. In some instances, the rainfall starts normally, but intermittent draught of 7- 20 days between two showers prevail. The average annual rainfall recorded during the last 50 years is 1375.20 mm.

3.3.3. Humidity

The air is highly humid through the southwest monsoon season. Afterwards, the relative humidity decreases gradually. The summer season is the driest part of the year, with an average relative humidity of about 45% in the morning and about 20- 25% in the afternoon. Relative humidity increases later with the progress of the season.

3.3.4. Wind

During the summer, hot westerly wind from Central India flows into the tract, causing exceptionally high day temperatures. This hot wind continues to blow more or less throughout the summer until the south-westerlies gradually replace it from the beginning of June when the temperature slowly falls. This was followed by a transition period until mid-November when the northerlies set in. The north wind blows till the end of February when it changes to the pleasant southerlies. The monsoon is characterized by Cyclones, which mainly originate in the Bay of Bengal and proceed towards the north. These are at their worst during the retreat and onset of the Southwest monsoon in Northern India.

3.4. Flora

The rainfall of the tract is a little above the lower limit of the rain for the North Indian moist deciduous forest and very near the higher limit of the Northern tropical dry deciduous forests. The favorable site conditions favor the development of wetter forest types even with lower precipitation. The forest of the Purulia district has different types of floral composition. The blank areas within the forest or degraded patches are regenerated artificially with the miscellaneous species. The rainfall is slightly above the lower rain limit for the North Indian Moist deciduous forests and very near the higher limit of the Northern tropical dry deciduous forest.

The main species in this forest is *Shorea robusta* (Sal), with characteristics associated with *Pterocarpus marsupium* (Peasal), *Terminalia tomentosa* (Asan), *Anogeissus latifolia* (Dhaw). The other commoner species which constitute the Top Canopy and Second Storey are *Adina cordifolia* (Karam), *Alstonia scholaris* (Chatim), *Albizia* sp. (Siris), *Buchanania lanzan* (Piyal), *Butea monosperma* (Palash), *Dalbergia latifolia* (Shetisal), *Diospyros melanoxylon* (Kend), *Madhuca indica* (Mahua), *Holoptelea integrifolia* (Challa), *Salmalia malabarica* (Semul), *Acacia auriculiformis* (Akashmoni), *Mangifera indica* (Mango), *Phyllanthus emblica* (Amla), *Spondias pinnata* (Amra), *Alangium salviifolium* (Ankar), *Terminalia arjuna* (Arjun), *Fiscus religiosa* (Aswatha), *Terminalia bellirica* (Bahera), *Ficus benghalensis* (Bat), *Anacardium occidentale* (Cashew), *Ficus carica* (Dumur), *Gmelina arborea* (Gamar), *Termanalia chebula* (Haritaki), *Artocarpus heterophyllus* (Kanthal), *Tamarindus indica* (Tetul), and *Cleistanthus collinus* (Porasi).

The common shrubs are *Combretum decandrum* (Atari), *Flacourtia indica* (Bainchi), *Gardenia gummifera* (Bhurru), *Holarrhena antidysenterica* (Kurchi), *Lantana camara*, *Phoenix acaulis* (Bankhejur) and *Ziziphus* sp. (Kul). The common herbs are *Aristida*, *Chrysopogon*, *Imperata*, *Pollinia*, *Themeda* etc. The familiar climbers are *Combretum* *decandrum*, *Bauhinia vahlii*, *Butea superba*, and *Smilax zeylanica*. Apart from that, some medicinal species like *Ocimum americanum*, *Semecarpus anacardium*, *Calotropis gigantea*, *Bombax ceiba*, *Azadirachta indica*, *Andrographis paniculata*, *Piper longum*, *Glycyrrhiza glabra*, *Centella asiatica*, *Acacia lenticularis*, etc. also notice with natural vegetation.

3.5. Fauna

This District was rich in fauna about 100 years ago and had evidence from old records, but at a speedy rate at which wildlife had disappeared in the last fifty years or so. Before the District was opened by Railways and the extension of cultivation to the wooded lands, different animals, notably tigers, leopards, bears, pigs, and Deer, were quite common.

Annual forest fires, hunts arranged by tribal people at frequent intervals, and coppice felling at short intervals have mainly caused this depletion. The paucity of water in the forest areas, the absence of water in the forest areas, and ground vegetation on the forest floor also contributed significantly. Wolves and Hyenas are frequently found in forests bordering the villages. Jungle Cat (*Felis chaus*) and Fox (*Vulpes bengalensis*) are uncommon. Now, Barking Deer (*Muntiacus muntjak*) is reintroduced in some pockets but Hares (*Lepus nigricollis*) are common and abundant. Mammals are observed such as *Macaca mulatta* (Bengal Monkey), Common Flying Fox (*Pteropus giganteus*), Common Palm Civet (*Paradoxurus hermaphroditus*), Fishing Cat (*Felis viverrina*), Indian Civet (*Viverricula indica*), Indian Pangolin (*Manis crassicaudata*), Jackal (*Canis aureus*), Leopard Cat (*Prionailurus bengalensis*), Palm Squirrel (*Funambulus palmarum*), Wall-roosting mouse-eared Bat (Myotis mystacinus muricola). At present, wild elephants (*Elephas maximus*) are seen in the forest; in most cases, they migrate from the nearby Dalma Wildlife Sanctuary.

The avifauna could be better. Among birds, it is worthwhile to mention grey and black partridges, a few varieties of ducks, storks, snipes, and teals. Definite information on Jungle Fowl needs to be included. Indiscriminate destruction of the game by aboriginal tribes seems to have harmed the resident population, and all except the migratory birds and other indigenous birds have decreased. Still, some birds can be noticed, such as

Green Magpie (*Cissa chinensis*), Jungle babbler (*Turdoides striatus*), White-throated bulbul (*Alophoixus flaveolus*), Black-headed Cuckoo strike (*Coracina melanoptera*), Common mayna (*Acridotheres tristis*).

3.6. Kangsabati South Forest Division

Kangsabati South Forest Division (KSFD) is in the southern part of the Purulia district in West Bengal. It is situated in the western corner of West Bengal, surrounded by Jharkhand, Bihar, and Bankura, Midnapore district. The forest division is situated between 23010'0"- 22050'00" North latitude and 86040'0"- 8700'0" East longitudes, covering 310.27 square Km/ 28559.30 ha areas (Fig. 3.2). It consists of six forest ranges- Bandwan-I, Bandwan-II, Jamuna, Manbazar-I, Manbazar-II, and Barabazar (Fig. 3.2). Biogeographically, this division represents Decan Peninsula Chhotonagpur (Zone 06B) and covered, by Dry Deciduous Forest (5B/C 1C). Most coppice of the area is Sal forest with miscellaneous tree species like – Mahul, Kend, Asan, etc. Native people depend on forests for timber, firewood, NTFP, and medicinal plants. All six ranges of KSFD were sampled (Fig. 3.3), but avoided sampling the extreme northern part of the division due to extensive human settlement and deforestation.

Bandwan-I Range- Bandwan-I range is spread over 5,154.61 ha. Consisting of two beats- Bandwan and Pargora- the total forest cover area is 5154.61 ha. It is located in the southwest region of KSFD.
Bandwan-II Range- This range is located in the Southern part of KSFD. It consists of two beats- Kuchia and Latapara- covering a total area of 3573.03 ha.
Jamuna Range- This is the largest range of KSFD covering 6636.51 ha areas of the southeastern part of KSFD, consisting of three beats- Kuilapal, Dhadka, and Nanna.
Manbazar-I Range- It consists of three beats- Manbazar, Sindurpur, and Kendra, covering 4234.97 ha of KSFD. This range is a north-eastern region of the division.
Manbazar-II Range- This range is spread over 3906.22 ha and situated at the central part of the division. This range consists of two beats- Kumari and Jamtoria.

Barabazar Range- This range covers 5053.96 ha, consisting of three beats- Bamundiha, Barabazar, and Sindri. Barabazar range is spread over the northwestern region of the KSFD.

Agro-ecosystem

The main polyculture is utilized in the agro-ecosystem of KSFD to avoid crop failure and increase income. Rice is the dominant crop in this area, and vegetables, legumes, and oilseeds are also cultivated. Almost the whole percentage of the population is engaged in commercial agriculture practice. Therefore, many chemical fertilizer inputs, inorganic pesticides, and mechanization were used to maximize crop production. This area is dominated by large farms, and small farms are generated with the help of large farms. Organic agriculture practices are primarily unknown to local farmers, with only a few workshops attended by farmers to incorporate organic methods. Agricultural products are primarily retailed by farmers in the neighboring States Jharkhand and West Bengal Government Agriculture Market (Mandi).

3.7. Research questions and objectives of the study

The investigation of the bee community composition in the agroforestry ecosystem across the KSFD was intended by this research. Through this study, an effort was made to compile a list of bee species in both agriculture and forest ecosystems and their interaction with plant functional groups in the study site. The primary intent of this study was to address the following research question.

I. How do anthropogenic activities affect the bee community?

II. How do bees play a role in crop productivity?

With this aim, research questions were answered through the following objectives.

Objectives I – To analyze the diversity of local insect pollinators in study areas and determine the effect of agriculture intensification on pollinator diversity.

Objectives II – To understand the ecosystem services of wild bees in the agroecosystem in contrast with anthropogenic activities.

Objectives III – To determine the role of non-crops in sustaining the pollen networks.

3.8. Period of the Study

In order to study, intensive field research was conducted in KSFD from February 2020 to April 2023. Sampling was carried out by adapting the sampling design to cover forest and agriculture ecosystems in all six ranges of KSFD. Field surveys were interrupted, due to the COVID-19 pandemic, the government of India imposed a lockdown and some restrictions.

3.9. Methodology: Sampling Design and Techniques

The study was conducted in selected seven unique plots for each of nine crops individually (n= 63), i.e., Mustard (*Brassica juncea*), Pigeon pea (*Cajanus cajan*), Cucumber (*Cucumis sativus*), Sunflower (*Helianthus annuus*), Sesame (*Sesamum indicum*), Green Gram (*Vigna radiata*), Ridge Gourd (*Luffa acutangula*), Eggplant (*Solanum melongena*), and Tomato (*Solanum lycopersicum*) and 32 forest patches, including mixed forest and Sal forest, covering a total of 95 survey sites (Fig. 3.4.). The observation was performed at three time hours, i.e., 8.30-9.30hr, 11.30-12.30hr, and 15.30-16.30hr., and standardized for use across the seasons. The selection of agricultural land was centered on mono-crop cultivation, stretching over 100 meters. Bees were sampled along the 100×4 m belt transect in the different agriculture fields and forest patches. Each transect had five subsampling plots, each of 5×5 m dimensions (Fig. 3.1). The sampling was carried out during the peak flowering periods of the crops and natural vegetation. Since the peak flowering period coincides with the highest number of bee activities, data was collected to avoid biased results. Bees were sampled on each transect using both active and passive methods. Focal observation, visual observation using a transect walk, and net sweeping were included in the active methods. The passive sampling method was done with the use of colored pan trap. Most northern part of the study area was exempted to survey as it was characterized by high human settlement and small agriculture land.

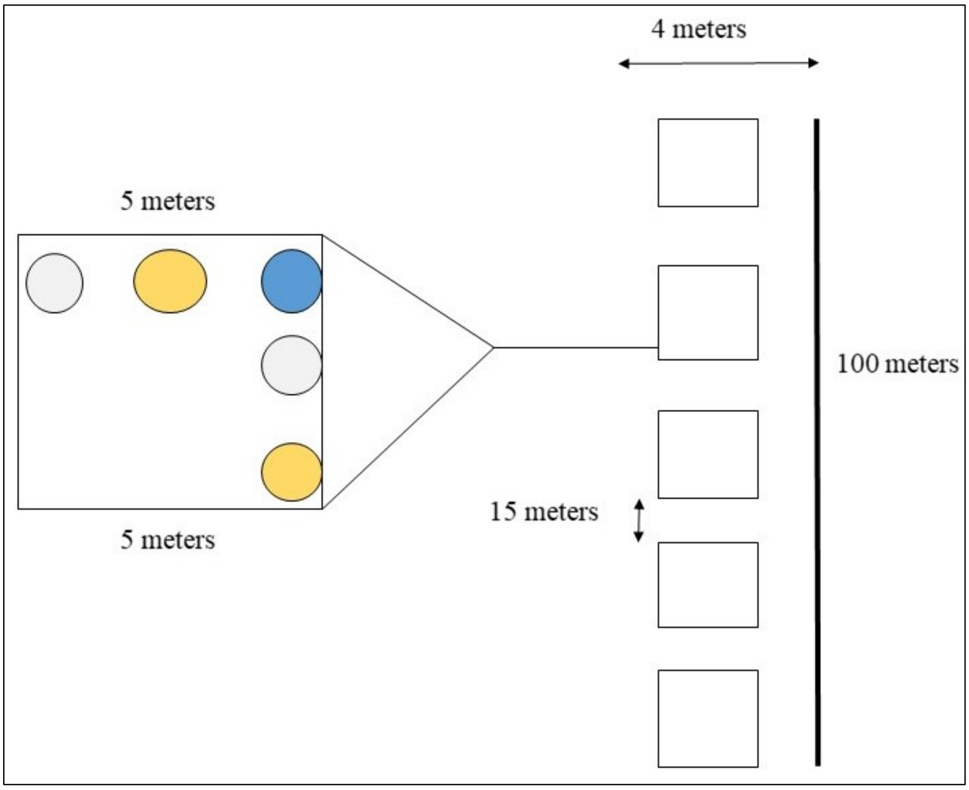


Fig 3.1. Belt transect for active and passive sampling methods to records bees. Yellow, white, blue pantraps in an enlarged sub-sampling plot.

3.9.1. Transect Walk

Belt transects were laid along the vegetation in different study sites, like vegetable fields and forest areas. The length of the line transects was 100 m. Observations were made on the flowers on either side, 2 m on each side (2m+2m= 4m); the study was conducted in seven plots for each crop and natural habitat in the peak flowering period. A predetermined transect path was followed through the study area (Sutherland, 1996).

3.9.2. Net Sweeping

Net sweeps were used to collect bee species for identification and pollen collection. I did not use net sweeping as a standardized sampling method.

3.9.3. Focal Observation

Visitors were observed in a 1-square-meter flowering area for 10 minutes (Gibson et al., 2011). Recorded the key behavior:

i. Time spent on each flower.
ii. No. of flowers visited in unit time.
iii. Whether it touches the reproductive parts of the flower or not.

3.9.4. Colored Pantraps

Pan traps (Westphal et al., 2008) were set in the flowering patch. Numerous pollinators are attracted by the color on the pan trap, and better estimates of anthophile diversity are provided when sampling with multi-color sets of pan traps. Yellow, white, and blue pan traps were painted with UV-bright colors. Five clusters of pan traps were established in a belt transect, where each cluster was separated by one another at a distance of 15m. Each sub-sampling pantraps (5×5 m) contain 15 pantraps of three different colors. As a result, 75 pantraps were placed along each belt transect, for a total of 475 sets of pantraps deployed in 95 plots (N=7125, three different colours of pantraps) spread across the study region. Pan traps were filled with clean tap water, and a drop of liquid soap solution was used to decrease the water's surface tension to drown the insects that landed.

3.9.5. Collection and preservation

Bees were sampled by sweep net and handpicking. Collected specimens preserved in 70% alcohol. Dry preservation was done by pinning or pointing and then drying and storing in an insect box (Gullan & Cranston, 2005).

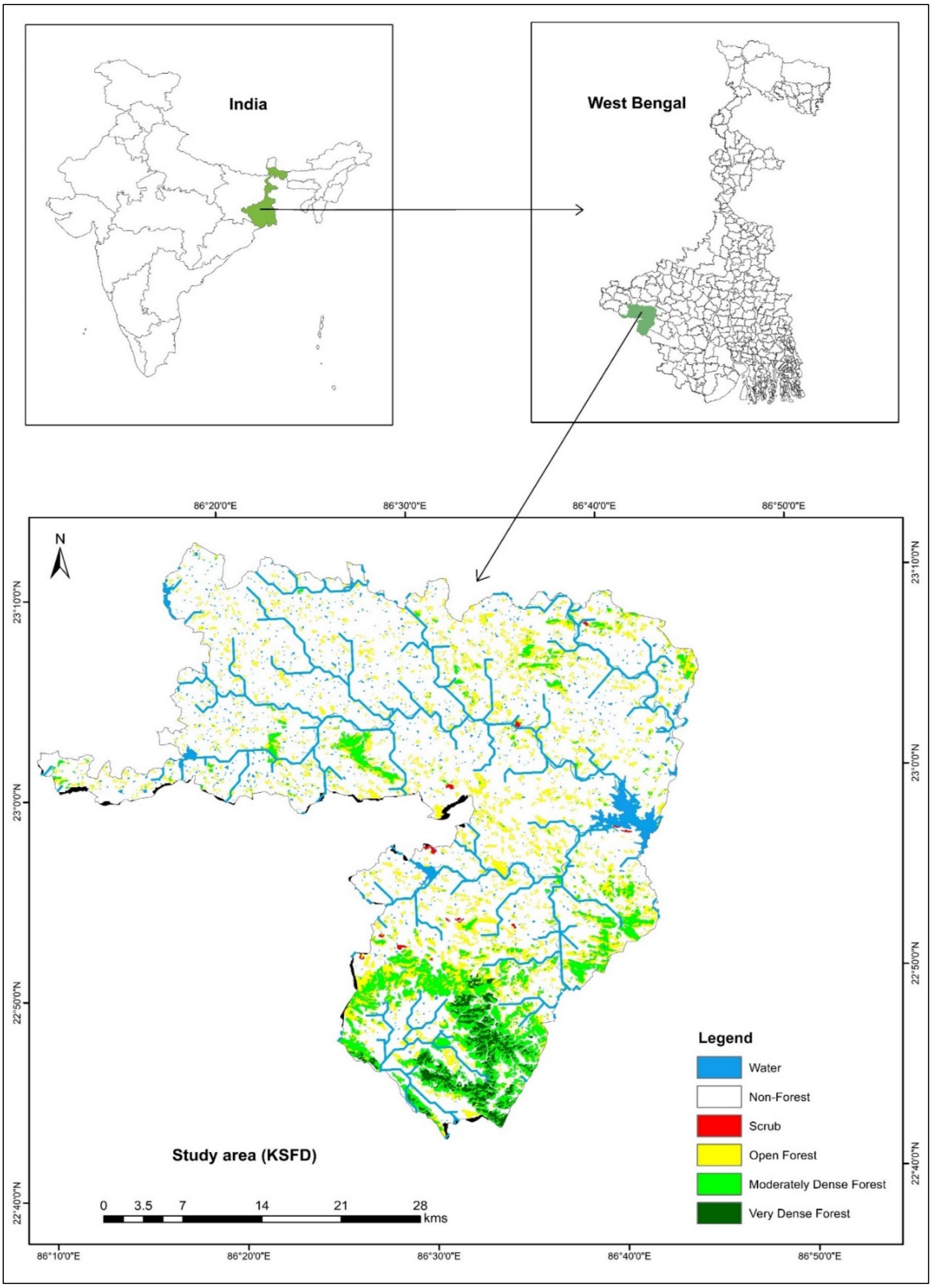


Fig 3.2. Map showing the study area KSFD.

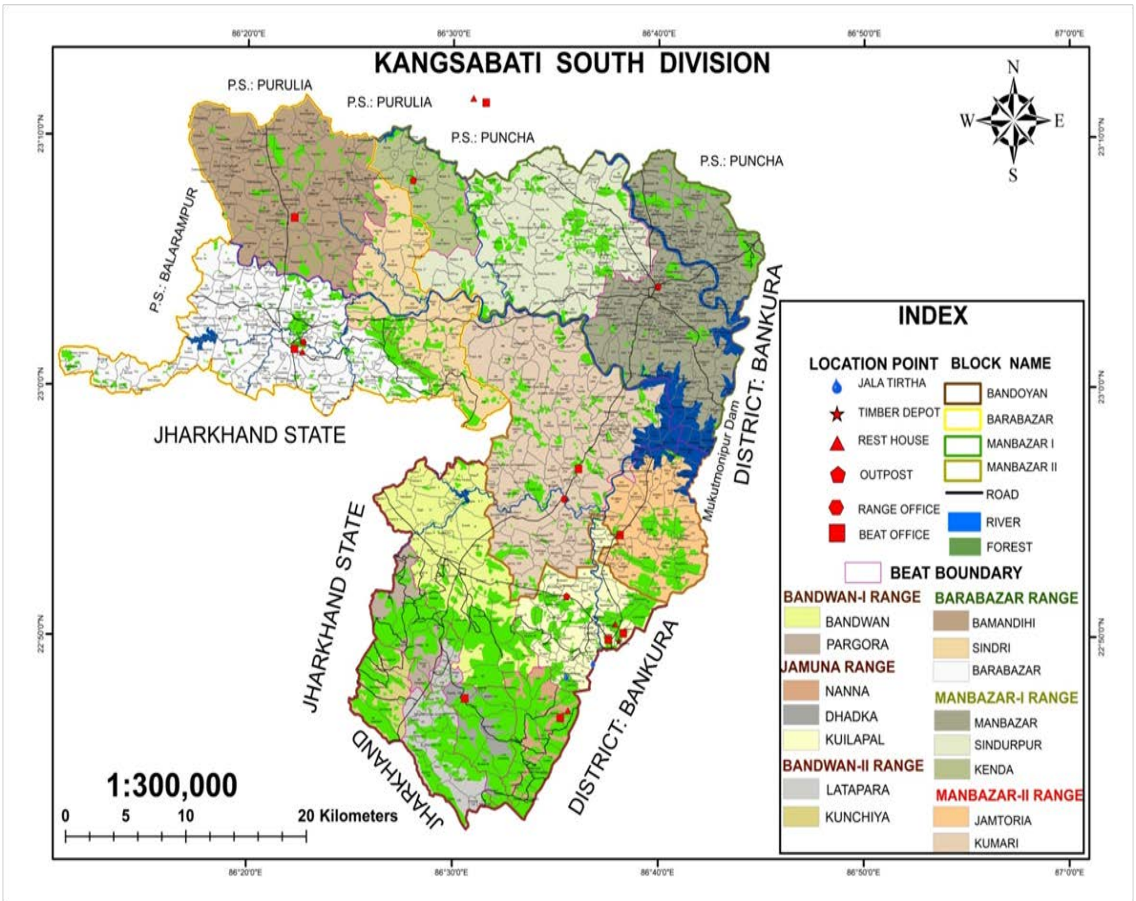


Fig 3.3. Range division of KSFD.

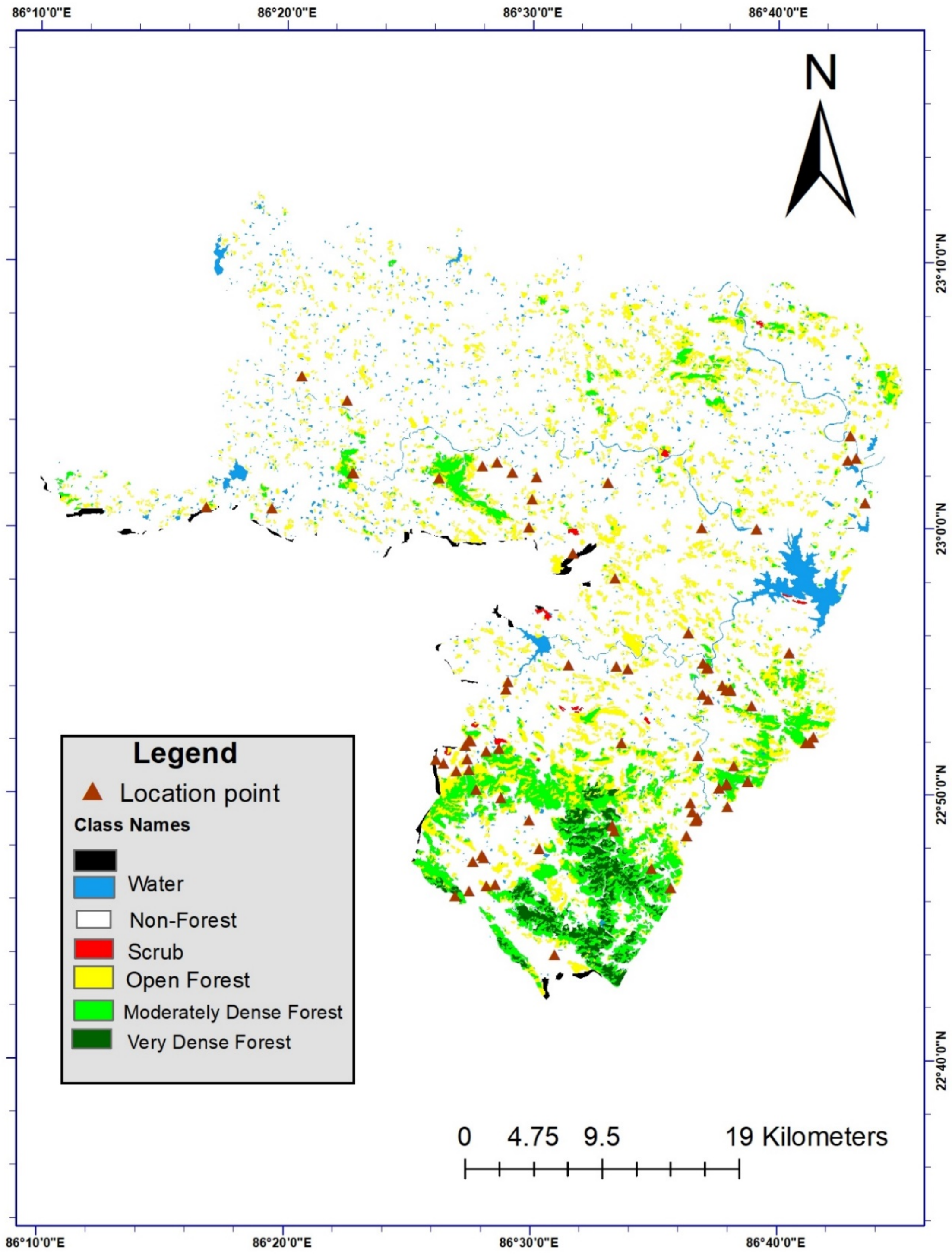


Fig. 3.4. Map showing 95 study sites.

Plate- 1

Forest Ecosystem

Plate- 2
Agro Ecosystem-Oilseed crops






Plate- 3
Agro Ecosystem-Vegetable crops



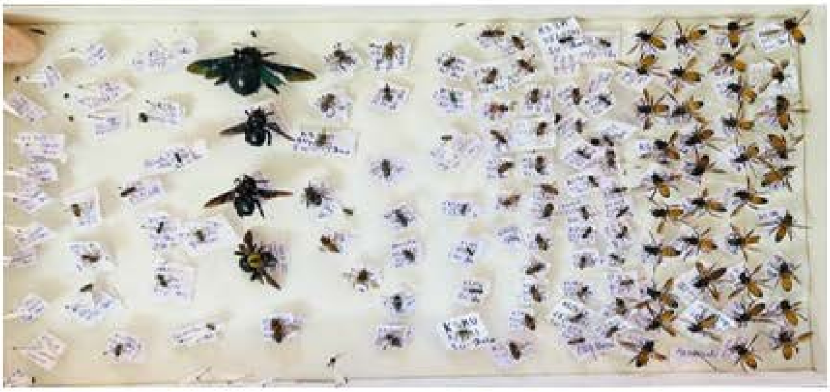

Plate- 4
Agro Ecosystem-Legume crops

Plate- 5

Methodologies







Chapter - 4

Diversity of local bee pollinators of study area KSFD

4.1. Introduction

Agroforestry is recognized as the practice of cultivating tree species and crops in intimate combination throughout the world (Steppler and Nair, 1987). The persistence of the wild bee population near forest areas adjacent to agricultural land is facilitated by the provision of a wide range of nesting sites. The most efficient pollinators, wild bees, are needed to pollinate some crops, requiring a "buzz pollinator." The phenology of flowers and seasonal and temperate trends are found to be correlated with relative bee abundance. A negative correlation between the abundance of solitary and social bees in an agroforestry ecosystem was identified by Klein et al. (2002). The gradual degradation of pollination services to crops and wildflowers, along with the conversion of forest areas to agricultural land, is attributed to pollinator decline, leading to this scenario. It was recommended by a case study in Orissa that 25% and 18% of natural vegetation cover adjacent to the eggplant and mustard agricultural lands, respectively, are needed for safeguarding future crop yield by pollination services (Chatterjee, 2020).

In India, 80% of the agricultural land depends on cultivating vegetables like eggplant, cucumber, and tomato. Among these vegetables, 70% of their production depended on the foraging activity of insect pollinators; as a result, 7.53 million tonnes of vegetables were produced in India, representing 13.4% of the global output. The fact that there was a declining yield growth rate for crops highly dependent on pollinators in developing countries has been highlighted by various studies. In India, the impact of pollinator loss would vary across landscape scales, agroecological regions, and situations (Basu et al., 2011). Due to this reason, it is crucial to recognize generalists and specialist pollinators across habitats to manage them sustainably for the natural and human-managed ecosystems.

Over the past half a century, attention has been to conserving and studying mitigation measures for honey bees due to a noticeable decline in the honey bee population.

However, after knowing the crucial roles of wild bees in crop pollination, emphasis investigations are directed to wild bees. The present study was conducted to gain baseline data on bees' diversity, which is hitherto unknown, as well as assess their status in forest and agricultural landscapes and also in various crops in Kangsabati South Forest Division (KSFD), Purulia, West Bengal, India. Here, an attempt was made to understand the richness and abundance of bee communities, encompassing wild and rare bees and social bees in both the agroecosystem and natural habitat. Additionally, an exploration was undertaken to determine the socio-economic conditions of the villagers and their familiarity with bees.

4.2. Methods: Sampling Design and Techniques

The investigation was conducted in agricultural land and forest areas, covering 95 survey sites (63 agriculture sites and 32 forest sites). Nine dominant crops in the study sites, i.e., Mustard (*Brassica juncea*), Pigeon pea (*Cajanus cajan*), Cucumber (*Cucumis sativus*), Sunflower (*Helianthus annuus*), Sesame (*Sesamum indicum*), Green Gram (*Vigna radiata*), Ridge Gourd (*Luffa acutangula*), Eggplant (*Solanum melongena*), and Tomato (*Solanum lycopersicum*) were chosen for the study. Bees were sampled using active and passive methods (Fig. 3.1) along each 100×4 m belt transect in the different agriculture fields and forest patches (mixed forest and Sal forest) of KSFD. Active methods were employed, including transect work, visual encounter, and focal observation. In a belt transect, five clusters of pan traps were established, where each cluster separated at a distance of 15m. Fifteen pantraps of three different colors were contained in each sub-sampling pantraps (5×5 m). Bees were collected and preserved in 70% alcohol. Dry preservation was done by pinning, pointing, drying, and storing in an insect box (Gullan and Cranston, 2005).

4.3. Identification of Species

A standard identification key by Bingham (1897) and Michener (1974, 1994, 2007) was followed for bee identification into families and morphospecies. The species-level identification at the Department of Zoology, Allahabad University, was conducted by bee taxonomist Dr. Jagdish Saini.

Key to the families of bees, on the basis of adults (Michener 2007)

1. Labial palpus with first two segments flattened, elongate, the last two segments small, usually separting laterally from axis of first two, rarely absent or not flattened; presence of stipitate comb and concavity commonly; galea comb absent or rarely weakly indicated; elongated galeal blade, often as long as or longer than stipes (Fig. 4.2); volsella mainly absent or tough to recognize, barely with distinct digitus and cuspis [L-T (long-tongued) bees] (Fig. 4.6)……………………………………………….……2

—. Four fragments labial palpus similar to one another, or first or rarely first two elongate but not much flattened; stipital comb and concavity absent; galeal comb commonly present; galeal blade normally shorter than stipes; Commonly well developed volsella, with recognizable digitus and cuspis [S-T (short-tongued) bees] …………………………………………………………………….…………….3

2(1). Labrum with enlarged basolateral angles, labrum thus widest at base, base forming broad articulation with clypeus; at least 0.8 times as long as broad and usually as long as broad or longer; scopa, when present, restricted to metasomal sterna; forewing with two submarginal cells (Fig. 4.4), generally about equal in length (except with three in Fideliini) ……………………………………………………….….…...Megachilidae

—. Labrum with basolateral angles less developed, articulation with clypeus thus narrower than full width of labrum; usually labrum is broader than long, except in some parasitic forms (where scopa is absent) labrum elongate; forewing with two or three submarginal cells, barely only one; presence of scopa on hind leg, particularly the tibia (Fig. 4.5), and usually absent on metasomal sterna; episternal groove absent (Fig. 4.3) ……………………………………………………..……………………Apidae

3(1). At apex glossa is pointed, occasionally with flabellum 4

—. Glossa bluntly rounded, flabellum absent, truncate, or bilobed at the apex (but pointed in males of three hylaeine genera from Australia-New Guinea area) ……………………………………………………………………….….............7

4(3). Lacinia characterized by scalelike lobe with hairs near base of galea; mentum and lorum form- ing proboscidial lobe, both at least partially sclerotized; lorum not flat ……... 5

—. Lacinia inconspicuous or displaced, not a scale-like lobe at the base of galea; mentum sometimes membranous, mentum and lorum not forming proboscidial lobe; lorum membranous or nearly flat sclerotized membrane (apron) between cardines 6

5(4). Lorum more or less platelike but created in central for attachment to base of mentum; fovea sometimes a groove rather than broad as in figure, facial fovea present in females and some males; subantennal area almost always defined by two subantennal sutures below each antennal socket (Fig. 4.1) …………………………...…………....…Andreninae and Panurginae (Andrenidae)

6(4). Small lacinia present and hairy lobe present on anterior surface of labiomaxillary tube above rest of maxilla a single subantennal suture beneath each antennal socket; first flagellar segment much shorter than scape; stigma well developed ………………………………………………………...…..…................ Halictidae

7(3). Apex of glossa truncate to bilobed (exclude pointed in males of three genera in the Australia-New Guinea region); scopa, when present, well developed on hind femur as well as tibia; episternal groove usually present below scrobal groove; .... Colletidae

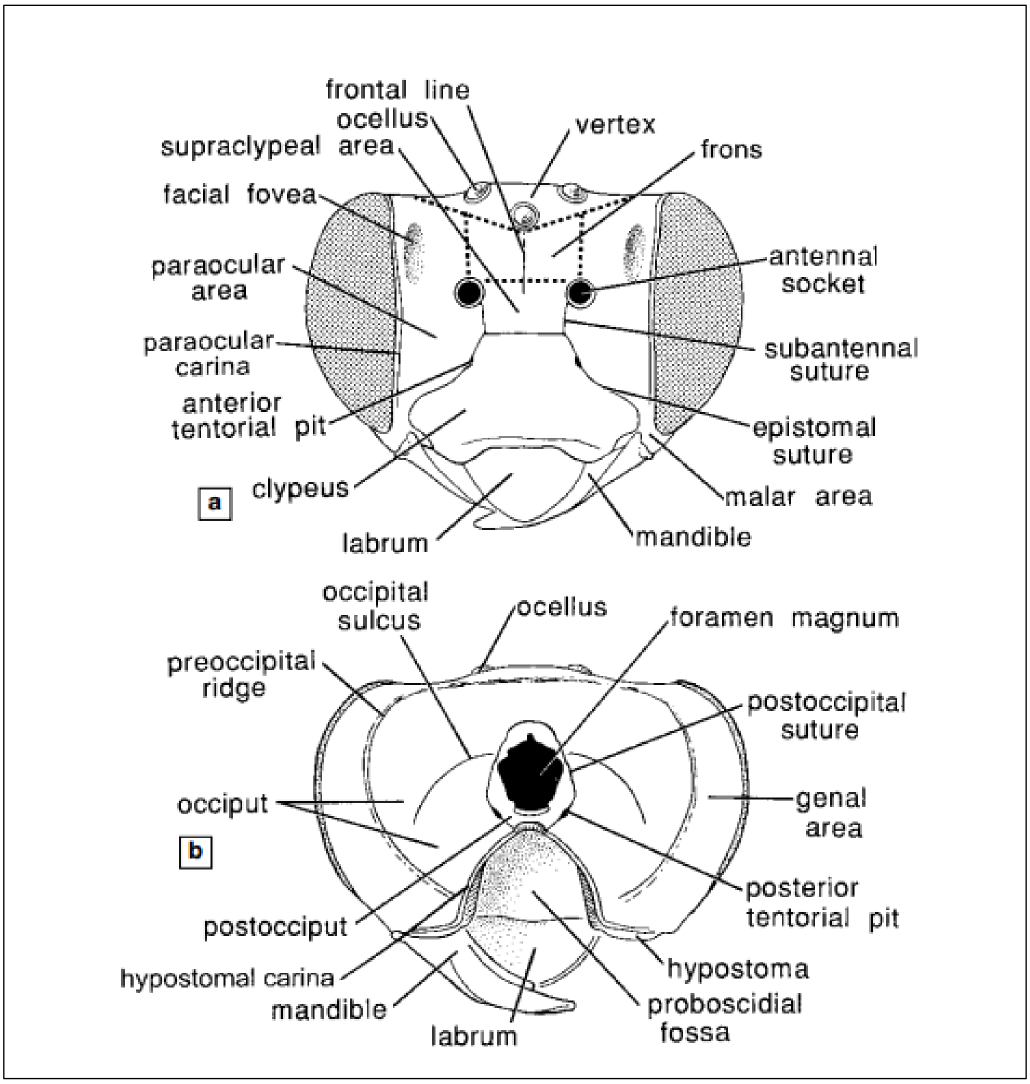


Fig. 4.1. Diagrams of a bee's head, showing major structures. **a**, Anterior view, **b**, Posterior view. (Michener et al., 1994).

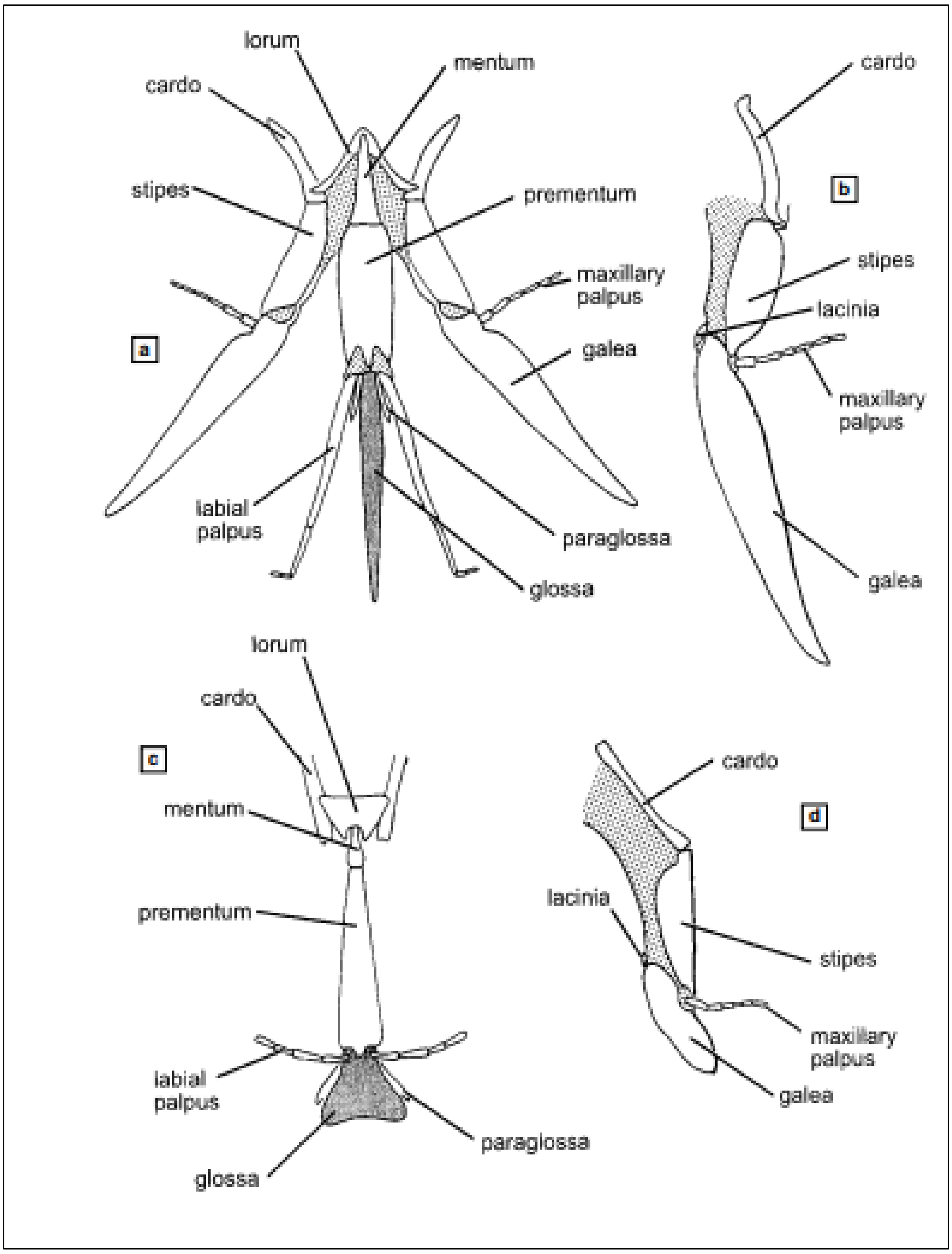


Fig. 4.2. Diagrams of proboscides of bees. **a.** Spread proboscis of a long-tongued bee, **b.** Maxilla of the same, **c.** Labium of short-tongued (here Colletid bee) showing portions of maxillary cardines at the base, **d**. Maxilla of the same (Michener et al., 1994).

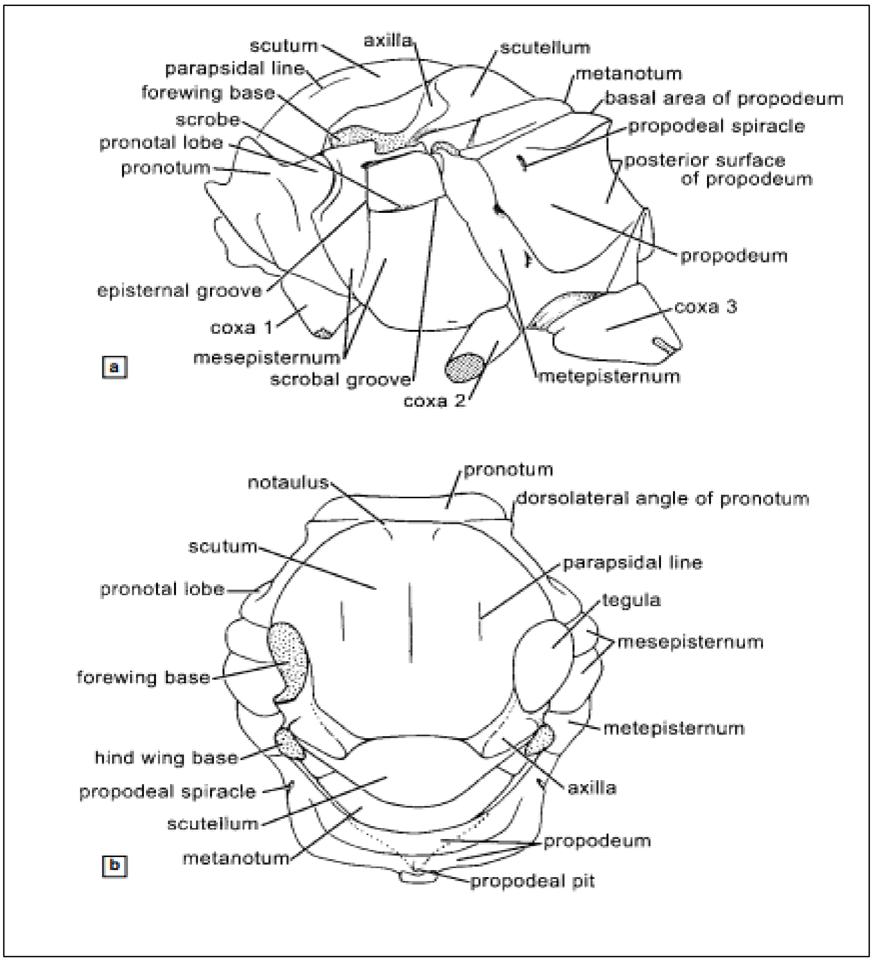


Fig. 4.3. Diagram of a bee's thorax, **a.** Lateral view, **b.** Dorsal view (Michener et al., 1994).

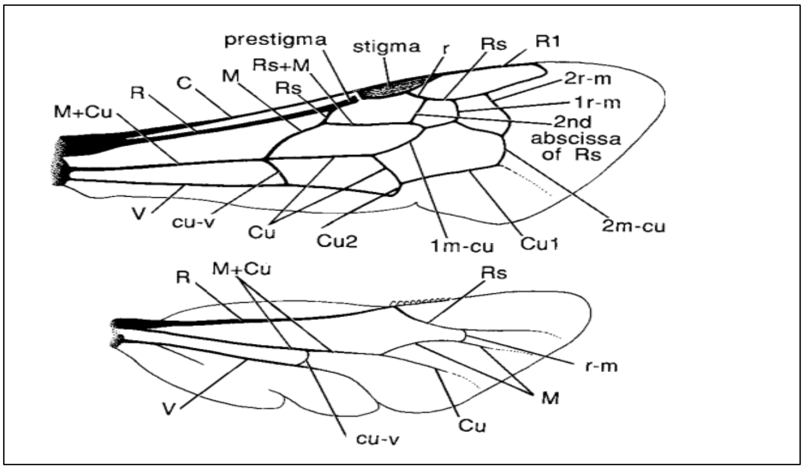


Fig. 4.4. Diagram of the wings of a bee, showing the vein terminology (Michener et al., 1994).

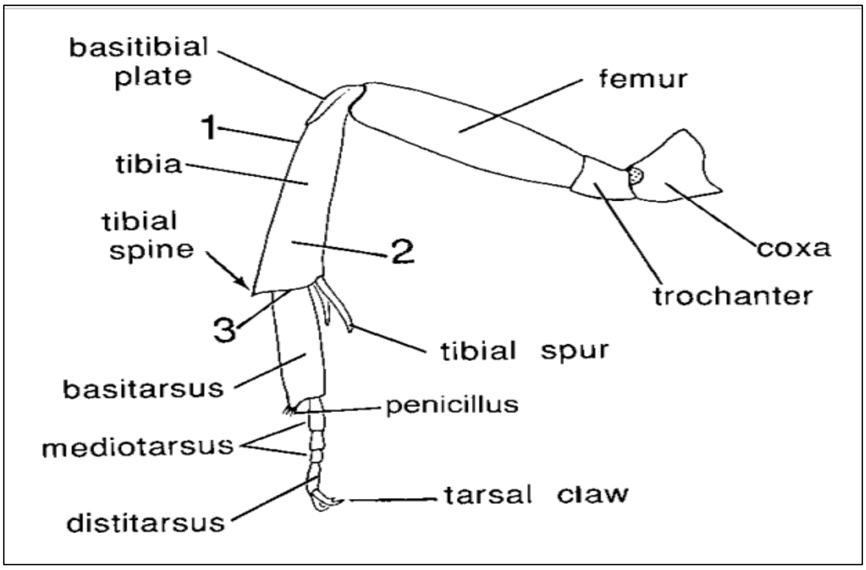


Fig. 4.5. Hind leg of a female bee, hairs omitted except those that from the penicillus. 1. indicates the posterior or upper margin of the tibia, 2. The outer surface 3. The distal margin (Michener et al., 1994).

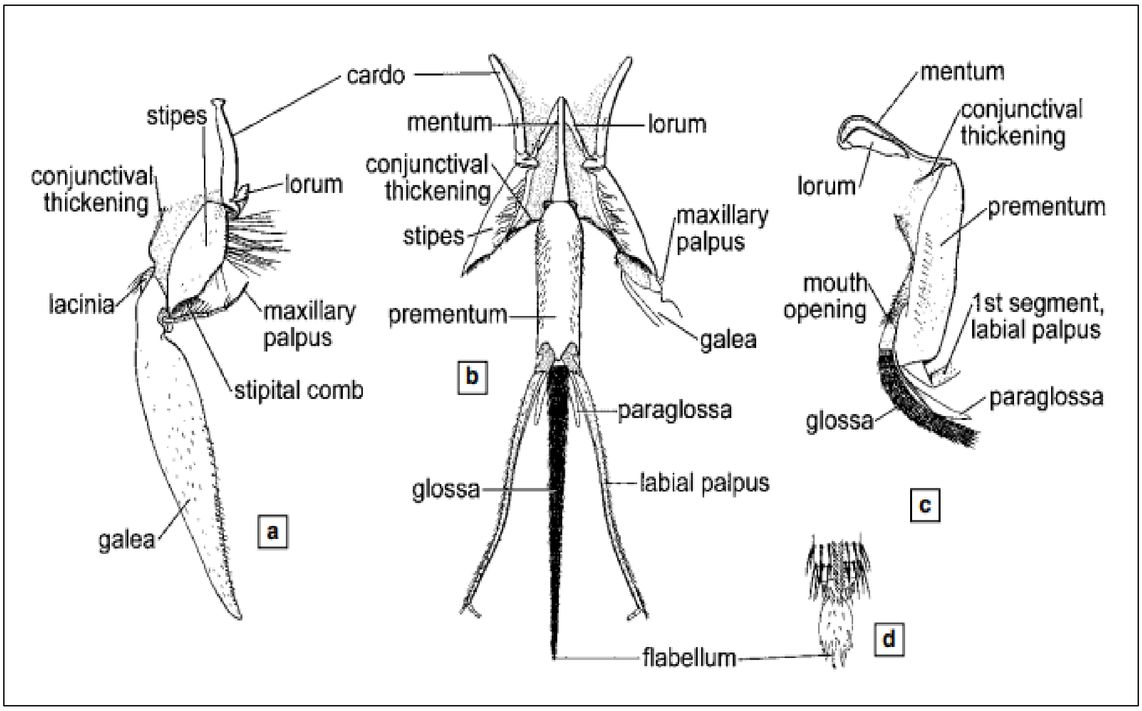


Fig. 4.6. Proboscis of an L-T bee (*Anthophora edwardsii*), **a.** Outer view of Maxilla, **b.** Posterior view of labium and basal parts of maxilla **c.** Lateral view of labium, the distal parts of the glossa and labial palpus omitted, **d.** Flabellum (Michener et al., 1994).

4.4. Data Analysis

4.4.1. Species diversity within the KSFD

The sampled (actively and passively) bees' data were pooled and computed to investigate species diversity patterns and richness across KSFD. The program data were analyzed using the "Vegan" package in R version 4.3.2. Bee species diversity was analyzed by the Shannon diversity index (H') and Simpson evenness.

Shannon Diversity Index (H’) = $-\Sigma pi * \ln(pi)$

Simpson evenness= $\hat{D}_{MAX} = \frac{1}{S}$

Accumulation curves were generated with the help of non-parametric estimators such as Chao- 1, Jackknife 1, Jackknife 2, and Bootstrap. Chao 1 is an abundance-based estimator is used to derive the species richness based on the number of rare species (Colwell & Coddington, 1994). In general, excellent performance is demonstrated by Jackknife's estimator in the extrapolation of the species richness, with finer precision, lower biasedness, and lower dependence on the sample size. The Jackknife 1 estimator is based on the number of species that occur in both exactly one sample and only two samples. Bootstrap estimator equation based on the proportion of sample plots containing each species. Although both Jackknife (1 & 2) and Bootstrap are as equally applicable for non-parametric estimators, the former were observed to perform better than the latter. Further, the comparison of the bee diversities between different habitats was essential. Data from active (transect and focal observations) and passive (colored pan traps) sampling methodologies were pooled.

4.4.2. Similarity in compositions of bee communities across habitats

The dependencies of bee species composition on their resource utilizations in the habitat have been noted (Chazdon et al., 2011). To test whether bee species composition in the habitats varied significantly, Bray- Curtis similarity (Brosi et al., 2007) was computed to check for similarity in species composition across the sites. Bray-Curtis similarity was a measure used to quantify the similarity of bee composition between habitats. The difference between habitats was measured by Bray- Curtis dissimilarity. The complement to the dissimilarity, provided by the Bray-Curtis similarity, was utilized. The advantage of using the Bray-Curtis similarity coefficient to represent inter-sample distance was that the contribution of each species could be quantified using similarity percentage analysis (Clarke, 1994). Hence, it is considered the most robust method for community similarity (Margurran, 2004). This similarity metric ranges from 0 to 1, where 0 indicates no similarity (entirely dissimilar communities), and 1 is represented by complete similarity (identical communities in species composition). Similarity values between three habitats- agricultural land, mixed forest, and Sal forest were observed, and the similarity of bee composition between crops was also noted.

4.4.3. Influence of meteorological parameters on abundance of bees

A significant influence was found between the abundance of bees and meteorological parameters like temperature, wind speed, rainfall, and relative humidity (Bhattacharyya and Chakraborty, 2016; Dorjay et al., 2017). To check how meteorological parameters influenced bee abundance, univariate linear regression analysis was opted for to see the relationship between the abundance of bees and meteorological parameters like; temperature (average), humidity (average), wind speed (m/s), and sky condition. Sky condition was classified into four categories – clear sky (0-25% cloud coverage), partly clouded (26-50% cloud coverage), mostly clouded (51-75% cloud coverage) and cloudy (76-100% cloud coverage). Surveys on rainy days were avoided to collect unbiased data. Linear regression, a fundamental statistical analysis used to project the value of a variable based on the value of another variable, was employed. The relationship between one or more independent variables (denoted as x) and dependent variables (denoted as y) was assessed by fitting a linear equation to the observed data. Linear regression is widely utilized in various fields for prediction, understanding relationships between variables, and making inferences based on data.

The general equation for a simple linear regression with one independent variable is:

$y = mx + b$

Where

y is the dependent variable.

x is the independent variable.

m is the slope of the regression line, representing the effect of the independent variable on the dependent variable.

b is the y-intercept, representing the value of y when x is zero.

4.4.4. Socio-economic survey

The data was collected at the community level through interviews. A hundred interviews were conducted in the community, which was equally divided into four existing economic groups, i.e., tribal, farmer, businessman, and government employee, which means twenty-five interviewees were selected from each economic group. During the questionnaire survey, it was ensured that a wide range of views and experiences were included, representing a diverse income group and livelihood types. Questioner surveys were held with knowledgeable people from the local community, and interviewees were selected based on their knowledge and relevance to the research questions. The questionnaire survey was conducted in a wide range of age groups, i.e., the old and elderly to the young generation of the study area. All the interviewees were educated at or above the primary education level. Specific questions were asked, covering household members, education status, source and status of income, cultivation area, cropping pattern, use of pesticides, dependencies of forest products, and usage of different forest products. A bee album was created to identify known bee species in the study area's population. While designing the questions, specific key points were kept in mind, like research questions, what we wanted to know, how we would answer, and avoiding ambiguous terms, long questions, technical terms, and negative questions.

Obtained information from the field and questionnaire survey was assumed to be accurate, as no bias was observed in the field survey and the choosing of the participants in the questionnaire survey. Cross-questioning was done to verify the data obtained in the questionnaire survey, thus marking the reliability of the information.

4.5. Results

A total of 7632 bee individuals were encountered, with 6510 individuals from the agricultural landscape, 756 individuals from the mixed forest, and 366 bees from the Sal forest. A sum of 25 bee species represented three families – Apidae, Halictidae, and Megachilidae. Three honey bee species were recorded (*Apis dorsata*, *Apis cerana*, *Apis florea*), one stingless bee species (*Tetragonula iridipennis*), 21 species of wild bees were recorded. The most abundant family was Apidae, covering 61% of the documented species, whereas the family Halictidae shared 31%, and only 8% was covered by the family Megachilidae in the studied area.

Table 1: List of the bee species recorded during the survey in KSFD.

Order	Family	Genus	Species
Hymenoptera	Apidae	*Apis*	*dorsata* (Fabricius, 1793)
			cerana (Fabricius, 1793)
			florea (Fabricius, 1787)
		Tetragonula	*iridipennis* (Smith, 1854)
		Xylocopa	*fenestrata* (Fabricius, 1798)
			aestuans (Linnaeus, 1758)
			magnifica (Cockerell, 1929)
		Ceratina	*smaragdula* (Fabricius, 1787)
			hieroglyphica (Smith, 1854)
			compacta (Smith, 1879)
			species
		Amegilla	*zonata* (Linnaeus, 1758)
			calcifera (Cockerell, 1911)
			violacea (Lepeletier, 1841)
		Thyreus	species
	Halictidae	*Nomia*	*elliotii* (Smith, 1875)
			crassipes (Fabricius, 1798)
			westwoodi (Gribodo, 1894)
			strigata (Fabricius, 1793)
			iridescens (Smith, 1857)
		Lassioglossum	species
		Pseudapis	*oxybeloides* (Smith, 1875)
		Lipotriches	species
	Megachilidae	*Megachile*	*lanata* (Fabricius, 1775)
			hera (Bingham, 1897)

4.5.1. Species diversity pattern within the KSFD

An asymptote curve was reached by the species accumulation curves for all recorded bee species across KSFD, representing different estimators like Chao, Jack 1, Jack 2, and Bootstrap. This estimated curve suggested satisfactory study completion was achieved through the sampling efforts. A pooled bee species richness of Chao 27, Jackknife1 28, Jackknife2 25, and Bootstrap 28 was calculated by the values of the estimators of the pooled data. However, it was explained by the habitat-wise species accumulation curves that bees in all three habitats, such as mixed forest, Sal forest, and agricultural landscape, were recorded adequately (Fig. 4.7- 4.10). During the study period, completeness of average 96.3% was demonstrated for the total documented bee species. Hence, 3.7% of bee species in the KSFD were not recorded. In the mixed forest, 88% of bees were recorded; 80% of bee species were documented in the Sal forest. At the same time, 74% of bees were recorded from agricultural landscapes. Rare bee species were recorded in the agricultural landscape, mainly in specific crops.

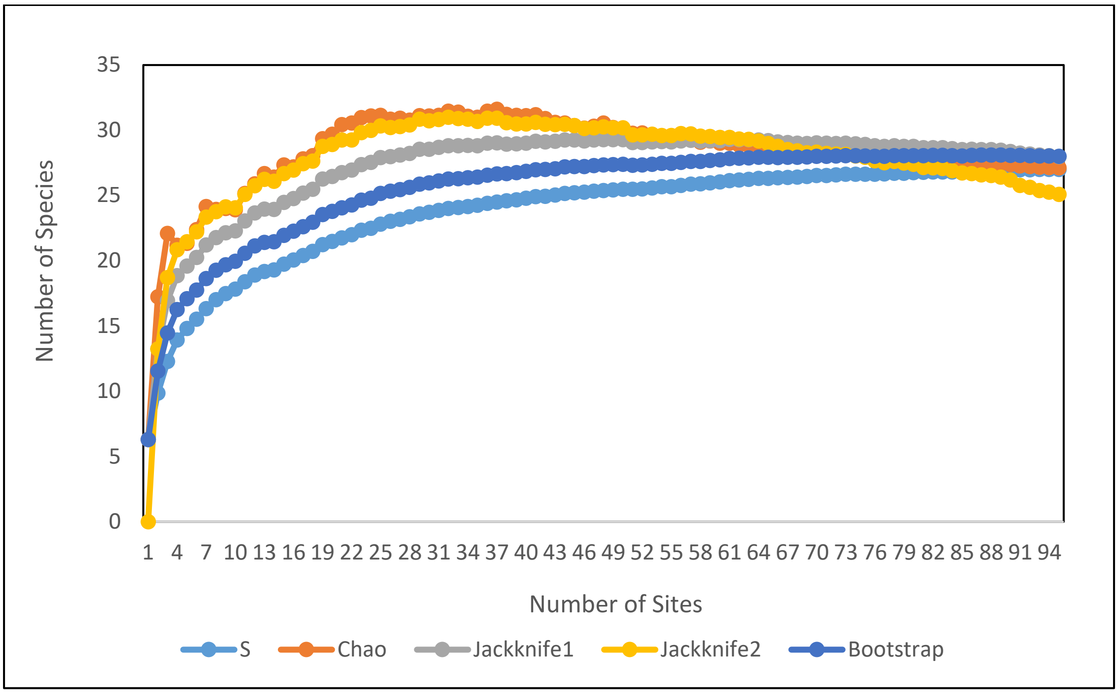


Fig. 4.7. Species accumulation curves of observed (Sobs) and estimated (Chao, Jackknife1, Jackknife 2, and Bootstrap) bee species across KSFD (all data pooled).

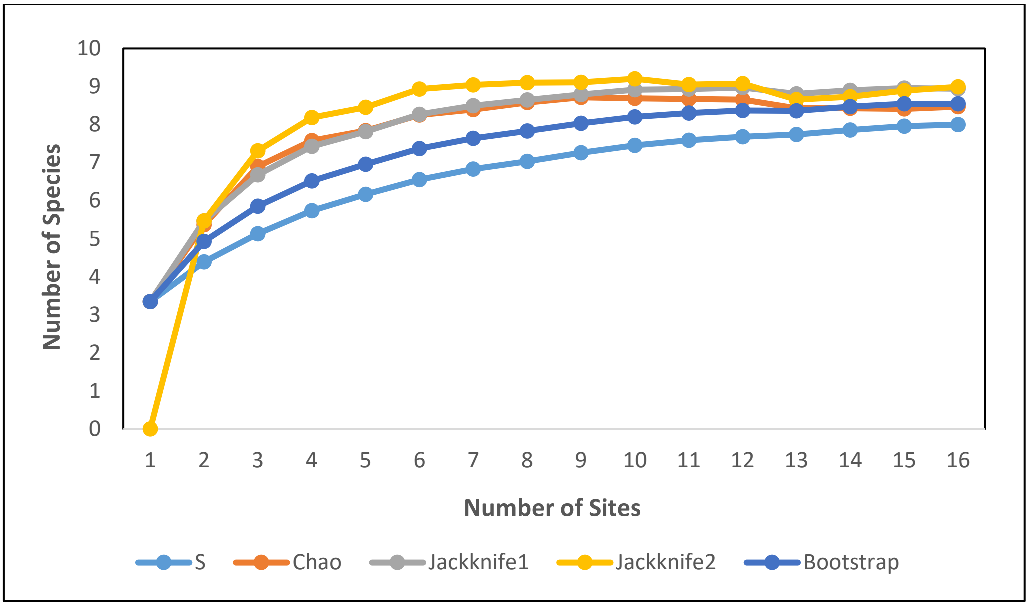


Fig. 4.8. Species accumulation curves of observed (Sobs) and estimated (Chao, Jackknife1, Jackknife 2, and Bootstrap) bee species in mixed forests across KSFD.

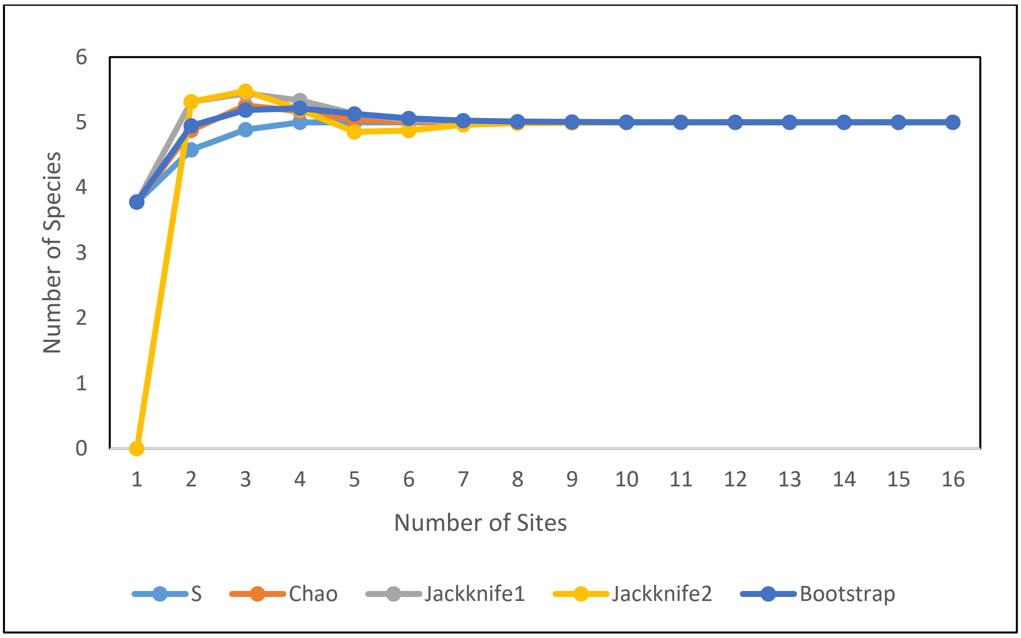


Fig. 4.9. Species accumulation curves of observed (Sobs) and estimated (Chao, Jackknife1, Jackknife 2, and Bootstrap) bee species in Sal forests across KSFD.

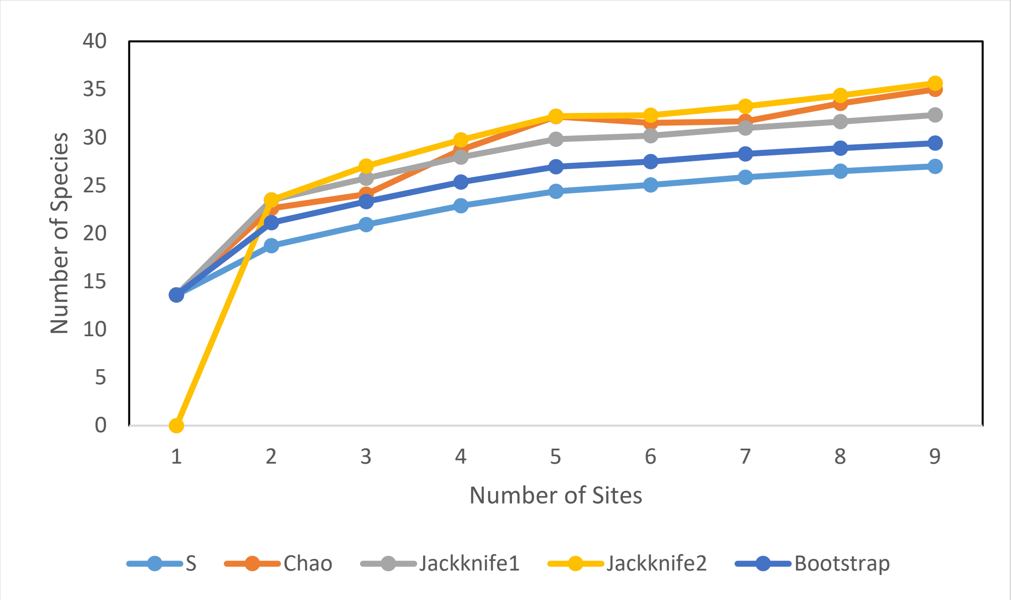


Fig. 4.10. Species accumulation curves of observed (Sobs) and estimated (Chao, Jackknife1, Jackknife 2, and Bootstrap) bee species in agriculture landscape across KSFD.

A low Shannon diversity index (Fig. 4.11) of bee species was observed in mixed forests, indicating a low diversity of bee species in the forest ecosystem. Simpson's evenness value of 0.3 was recorded in the mixed forest, suggesting low evenness in species abundance distribution. A moderate level of bee diversity (1.2) was noticed in the Sal forest, and a similarly moderate level of evenness (0.67) in the species abundance distribution was observed in the forest ecosystem. Comparatively, a higher bee species diversity value (2.2) and a higher level of evenness (0.82) in the distribution of bee species were noticed in the agricultural ecosystem.

In the agriculture landscape (Fig. 4.12), higher bee species diversity was observed in tomato (2.4) than in other crops, followed by high diversity observed in eggplant (2.2), ridge gourd (2.1) (Das & Uniyal, 2023), and green gram (2.1). A relatively moderate diversity of bee species was observed in sesame (1.7) and sunflower (1.6). Bee diversity in mustard, pigeon pea, and cucumber exhibited a relatively low level of diversity with a value of 1.4. According to Simpson Evenness, moderate evenness in distribution was indicated by bee species abundance in the crops pigeon pea (0.6), cucumber (0.66), green Gram (0.72), mustard (0.73), and sunflower (0.74). A high level of evenness in the distribution of bee species abundance was noticed in sesame (0.83), eggplant (0.84), ridge gourd (0.85), and tomato (0.87).

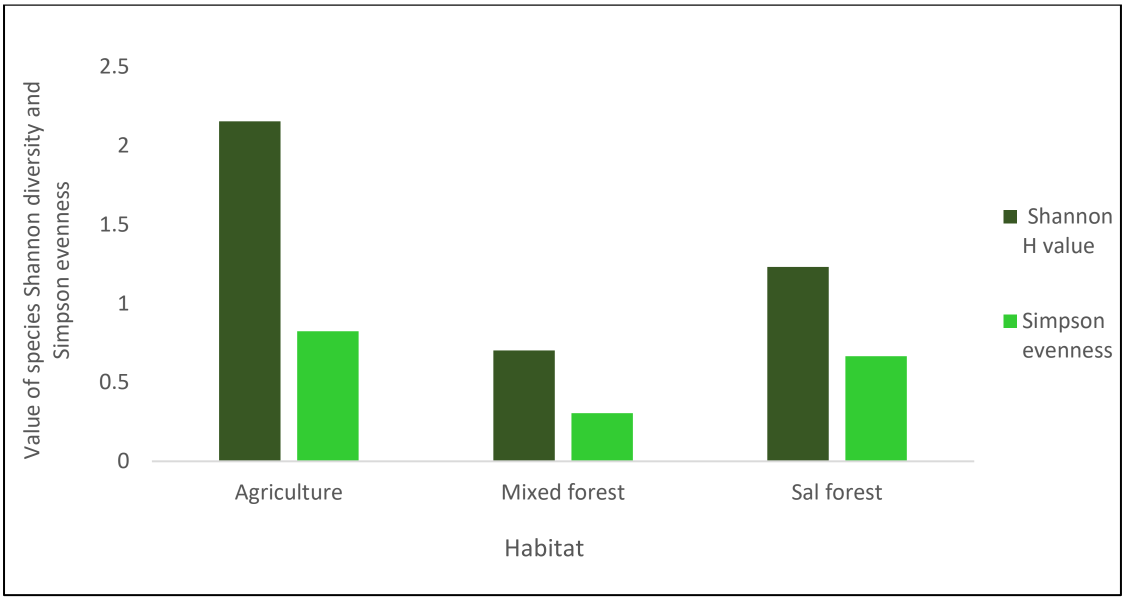


Fig. 4.11. Shannon Diversity Index and Simpson Evenness Index of bee species in different habitats in KSFD.

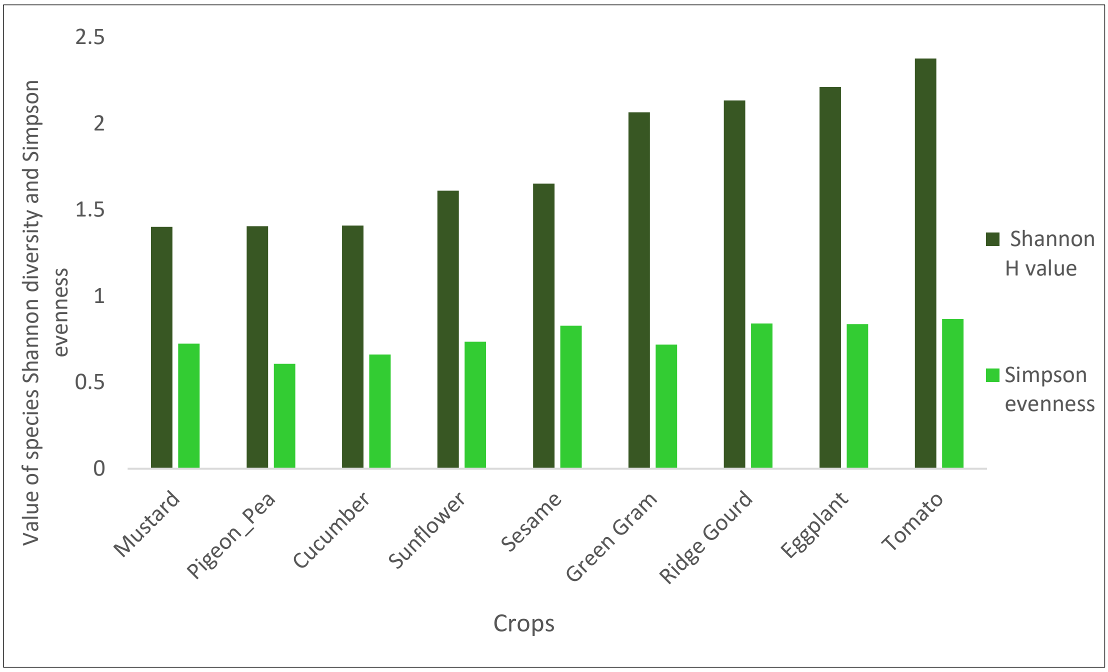


Fig. 4.12. Shannon Diversity Index and Simpson Evenness Index of bee species in different habitats in KSFD.

4.5.2. Similarity in compositions of bee communities across habitats

Bray-Curtis similarity value (Fig. 4.13) of 0.791 between agricultural land and mixed forest was obtained, suggesting a relatively high level of dissimilarity in species composition or abundance between these two habitats. Even higher dissimilarity (0.893) in species composition with agricultural land was shown by the Sal forest. The Bray- Curtis similarity value between mixed forest and Sal forest was 0.661, which was relatively lower than 1 but still above 0.5, suggesting a moderate degree of dissimilarity in species composition between these two types of forests though Sal forest dominated by Sal trees (*Shorea robusta*).

Regarding the similarity between mustard and other crops (Fig. 4.14), low dissimilarity (0.469, 0.429, 0.304, 0.494, 0.454, respectively) was exhibited by pigeon pea, cucumber, sunflower, green gram, and ridge gourd. In contrast, a moderate degree of dissimilarity was observed with sesame (0.627) and eggplant (0.659), and a high level of dissimilarity was observed with tomato (0.98). High dissimilarity with cucumber (0.78), sesame (0.716), and tomato (0.913) was observed in the bee composition of pigeon peas. Still, a moderate degree of dissimilarity was noticed with sunflower (0.45), green gram (0.49), ridge gourd (0.58), and eggplant (0.51). A moderate degree of dissimilarities with most of the crops and the value ranging from 0.384- 0.544 was shown by the Bray- Curtis dissimilarity value of cucumber with other crops, whereas a high degree of unlikeness was observed with green gram (0.714), tomato (0.862) and eggplant (0.901).

Dissimilarity values (Fig. 4.14) of bee composition in sunflowers with other crops had a low to moderate degree of difference ranging from (0.304- 0.582), but high levels of dissimilarities were observed with eggplant (0.661) and tomato (0.897). A high level of unlikeness between green gram (0.662), mustard (0.628), cucumber (0.716), eggplant (0.708), and tomato (0.76) was displayed by sesame while exhibiting a low level of dissimilarity with the rest of the crops. A moderate level with other crops was observed in the distinct value of the bee community in green gram, except for eggplant (0.693) and tomato (0.914). Similarly, moderate dissimilarity of bee composition with other crops was exhibited by ridge gourd, except eggplant (0.63) and tomato (0.805). A higher level of dissimilarity with all crops, except for pigeon pea (0.508), where bee composition was moderately unlikeness, was maintained by the eggplant. A similar trend was also observed in tomatoes; it showed a high degree of dissimilarity between every crop in the studied area.

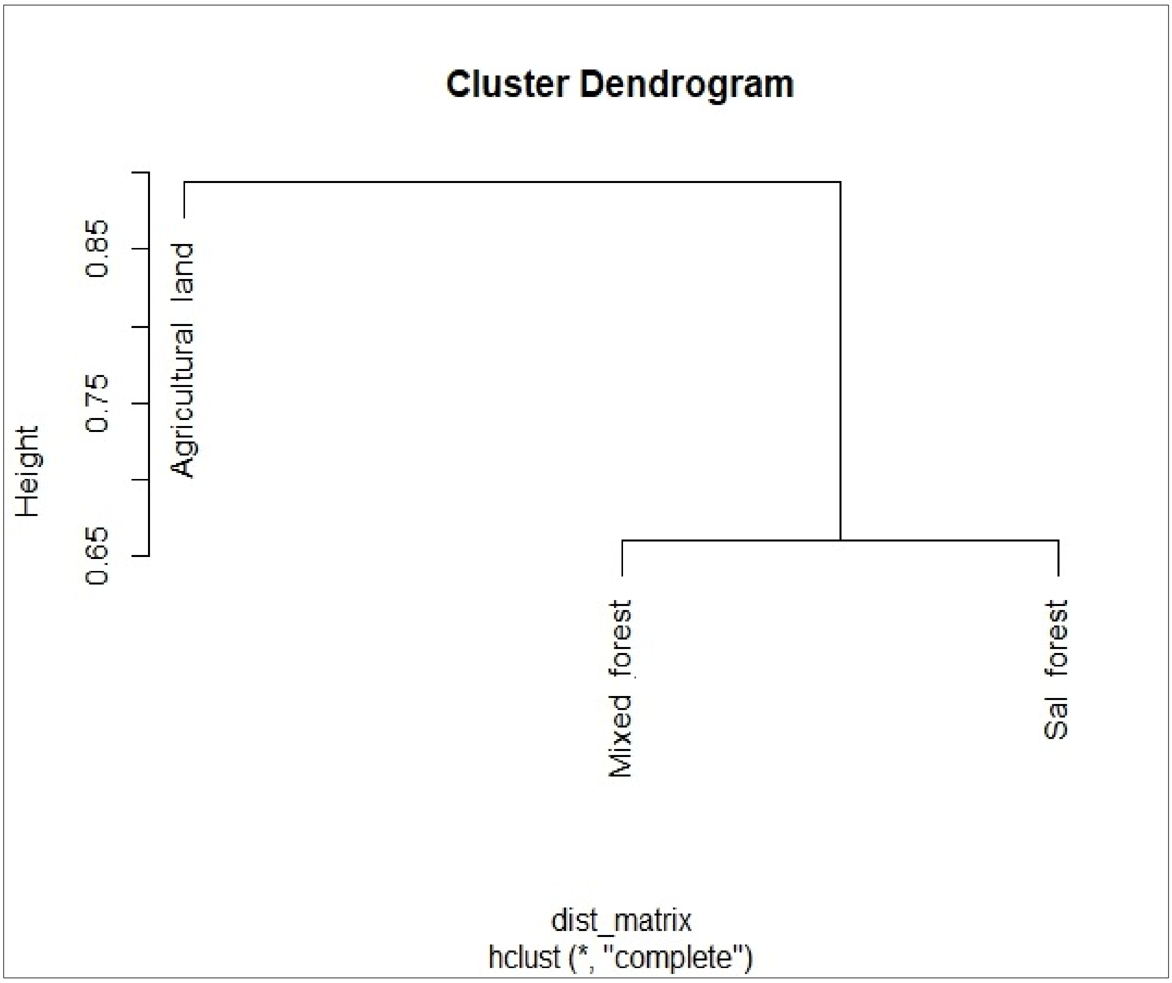


Fig. 4.13. Bray- Curtis similarity index of bee species in different habitats, Agriculture land, Mixed Forest, and Sal Forest of KSFD.

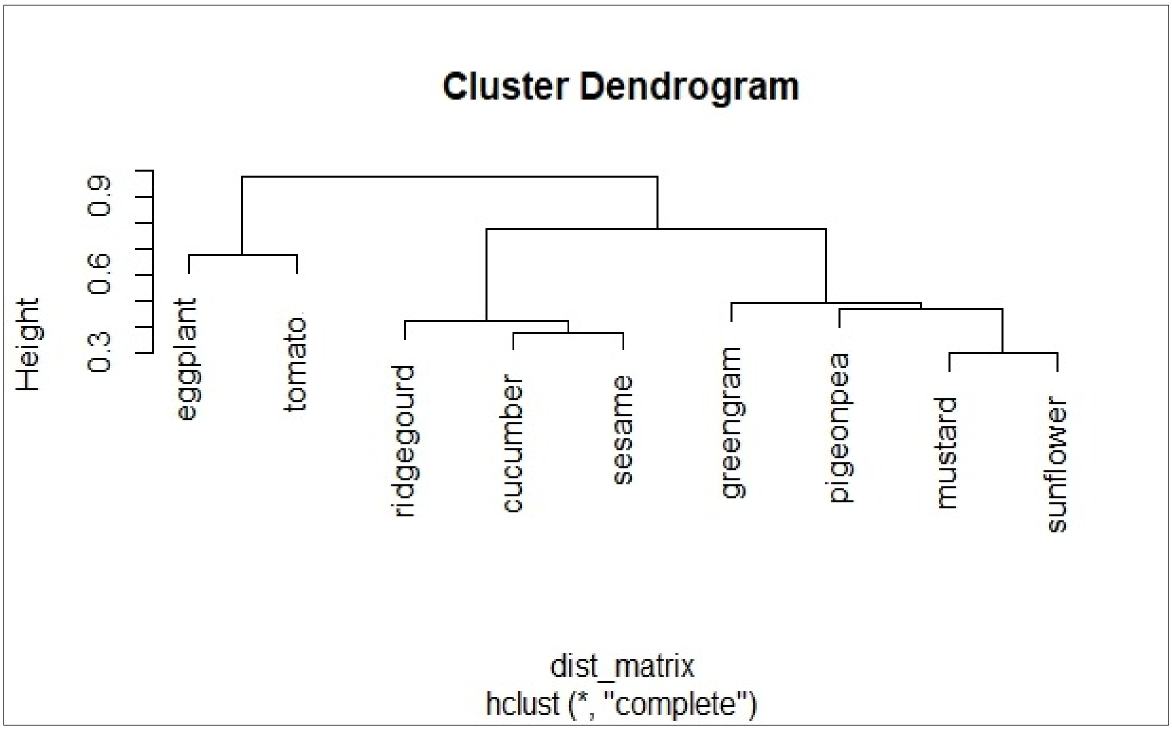


Fig. 4.14. Bray- Curtis similarity index of bee species in different crops in the Agricultural landscape of KSFD.

4.5.3. Influence of Meteorological parameters on the abundance of bees

Based on the measured value of bee abundance and meteorological parameters (temperature, humidity, wind speed, sky condition), the statistical correlation was determined; sampling during the rainy day was skipped for biased data (Bhattacharyya and Chakraborty, 2016; Dorjay et al., 2017). This experiment was made to understand whether there was an occurrence of any relationship between bee abundance and meteorological parameters (Fig. 4.15- 4.18). In the scatter plot for the correlation between bees' abundance and temperature, the plotted regression was observed to be ascending in direction (r^2= 0.0138).

The connection between wind and bee abundance was negatively correlated; the correlation coefficient was descending in the regression direction with an r^2 value of 0.0615. The scattered plot of correlation between sky condition and abundance of bees, calculated with decreasing coefficient value (r^2= 0.0615), indicated a negative association between sky condition and abundance of bees.

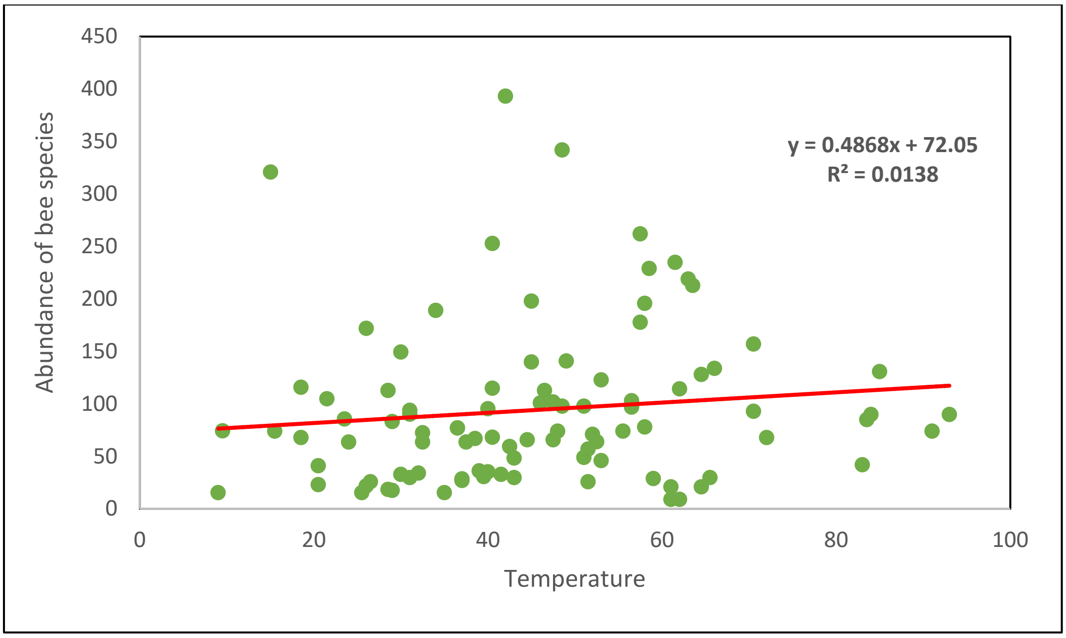


Fig. 4.15. Scatter plot with linear regression directed between the abundance of bees and temperature documented during the survey period in KSFD.

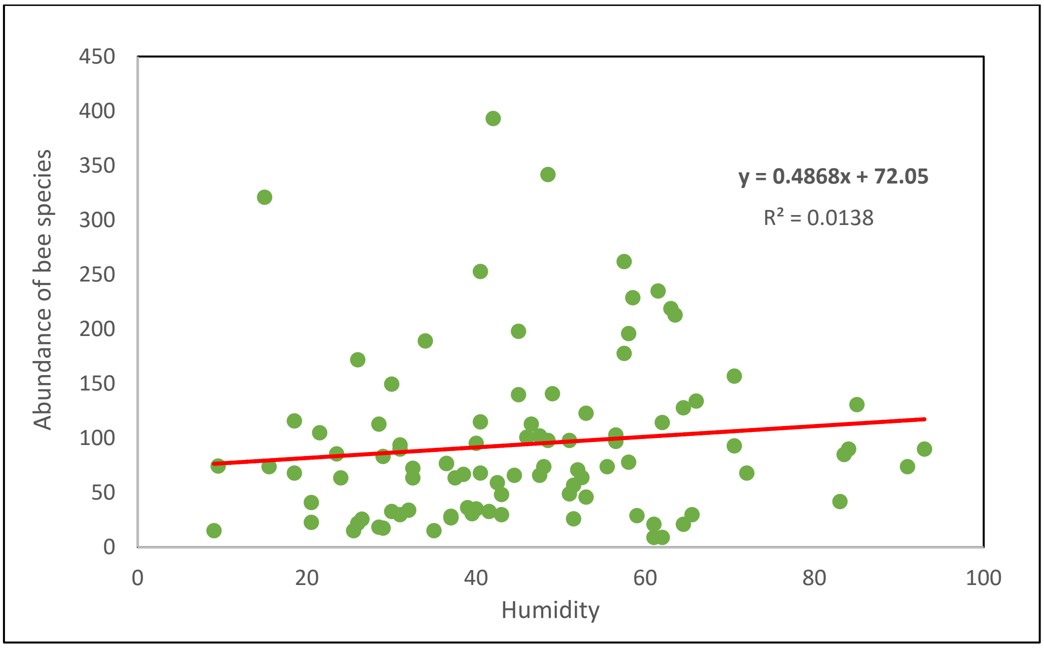


Fig. 4.16. Scatter plot with linear regression directed between the abundance of bees and humidity documented during the survey period in KSFD.

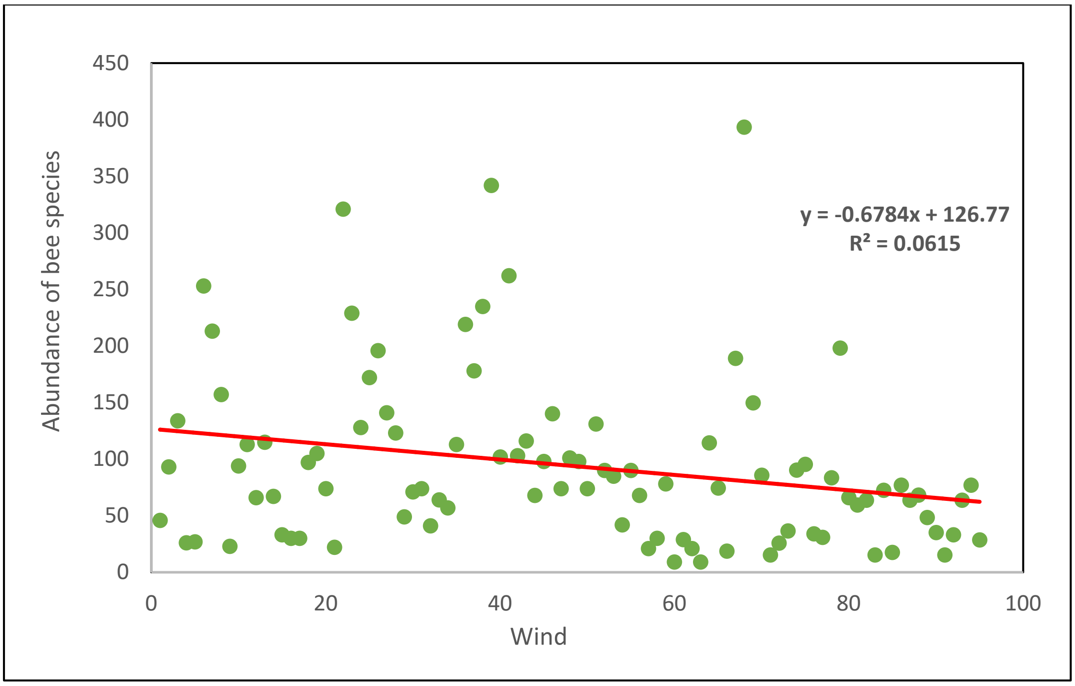


Fig. 4.17. Scatter plot with linear regression directed between the abundance of bees and wind speed documented during the survey period in KSFD.

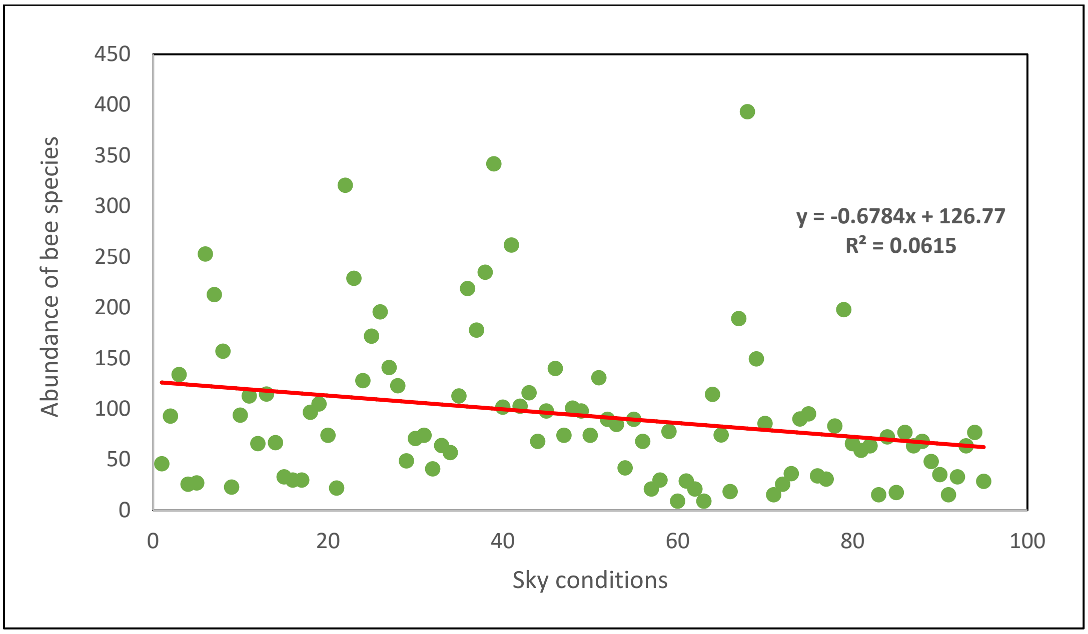


Fig. 4.18. Scatter plot with linear regression directed between the abundance of bees and sky conditions documented during the survey period in KSFD.

4.5.4. Socio-economic survey

The southern part of the Purulia district is primarily dominated by the tribal population, who are mainly dependent on agricultural activity. The farming system in the study area includes croplands and livestock, which are all linked to the surrounding forest biodiversity. The primary sources of income in the study area were agriculture practices; other than that, people were prone to contractual work and migration workers, and very few people were focused on governmental jobs (Fig. 4.19). Rice was the most popular cultivated crop, as the study area was drought-prone. Most of the year, large parts of unfertile degraded lands were converted from agricultural landscapes due to recurrent drought and low soil fertility. The main rivers of this area are Kangsabati and Kumari, which are seasonal. Vegetable crops cultivation is restricted only near the water bodies, as the agricultural practice of these crops requires a large amount of water.

A large number of Indigenous people in the study area were involved in unskilled agriculture practices, and the rest were interested in Government jobs and business. Secondary school-level educated Indigenous people were interested in being migratory laborers to the nearest district or state, especially in coalfields. In the present study, all surveyed tribal families were found to be under the poverty level (<5k/month) and were mainly involved in selling or using Non Timber Forest Product (NTFP). Some of their family members worked as migratory laborers, but due to COVID-19, their source of earnings was impacted. Except for a few indigenous families, others were involved in seasonal agriculture practices, especially rice cultivation, or contractual laborers were involved in other farmland. Apart from Indigenous people, villagers were engaged in agriculture practices and small and large-scale businesses, and few were interested in Government jobs. Most farmers and small-scale businessmen earned <=10k/month, 24% of the surveyed families. All surveyed government employees and large-scale businessmen have agricultural lands where contractual farmers were appointed for crops or rice cultivation.

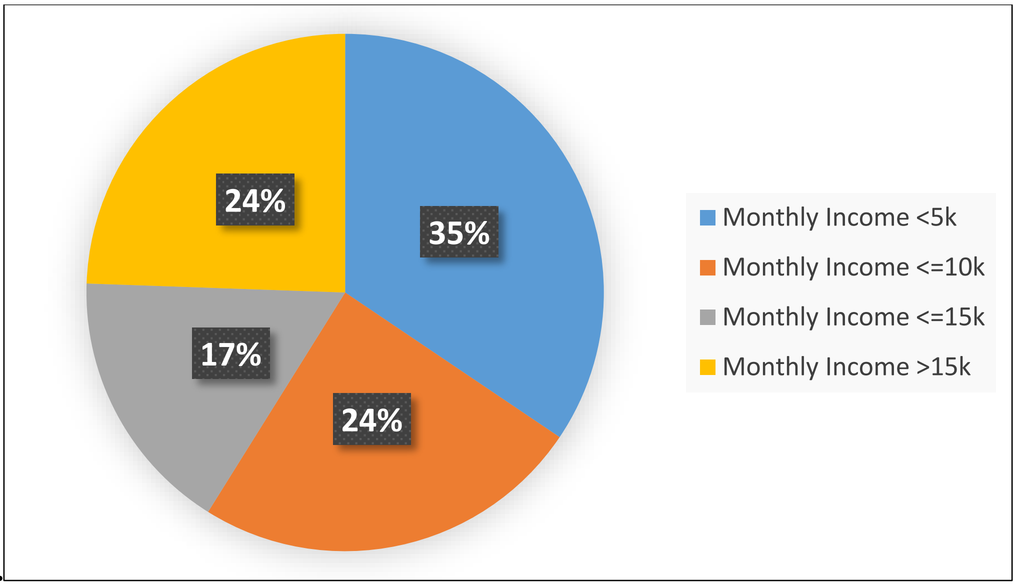


Fig. 4.19. Percentage of monthly income of the surveyed population in KSFD.

LPG as an energy source was limited to government-holder families, large-scale businessmen, and farmers' families, i.e., 25% of the surveyed population. Apart from this, families and firewood were depended upon by a large portion of the studied population (Fig. 4.20), and fuelwoods were extracted from the nearby forest patches. The fuel woods were used by small-scale hotels and tea stalls. Besides firewood, forests are also relied upon by these families for other resources. NTFP was utilized by these families for consumption and as a source of earnings. Fruits and vegetables like *Terminalia bellirica*, *Diospryros melanoxylon*, *Anacardiu occidentale*, *Ficus serica*, *Tamarindus indica*, etc., were used in households, and the rest were sold in the local market. The most popular NTFPs in this region were Mahua (*Madhuca indica*) flowers and leaves of *Shorea robusta*; these products have a good market value in nearby districts and states. Collections of fuel wood and NTFPs were mainly associated with women and children; sometimes, elderly people also joined in the collection process. Some people are also involved in honey extraction from the nature.

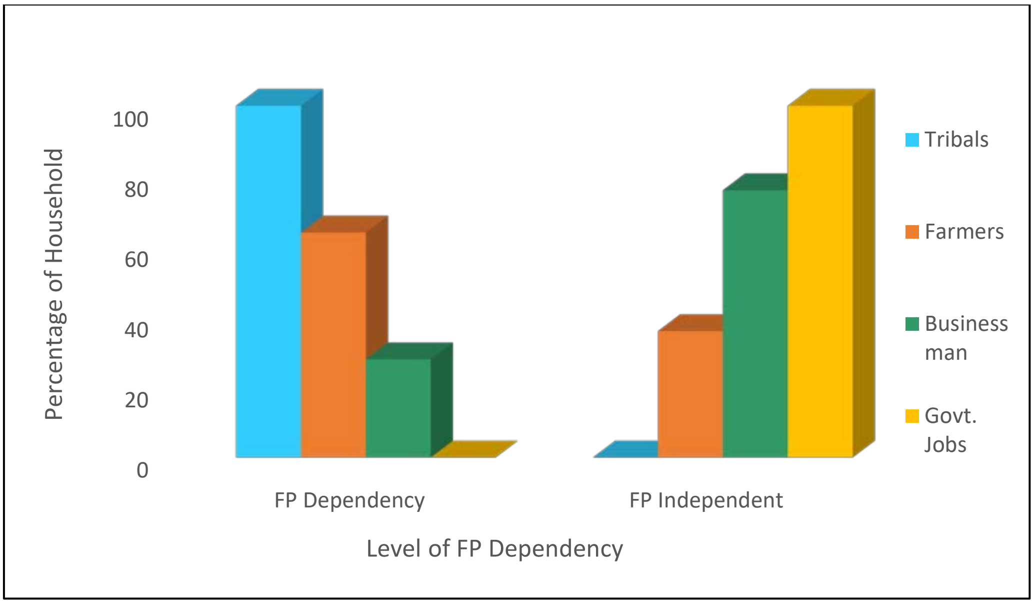


Fig. 4.20. Level of forest product dependency with the percentage of the household recorded in KSFD (FP =Forest Product).

The study sites were dominated by mixed cropping patterns, and inorganic pesticides were used simultaneously. Among the surveyed people, 36.25% of families had 1-3 acres of land, which is the highest; 18.75% of the population owned 5-8 acres of agricultural land, and 13.75% possessed more than 8 acres. Farmers were unaware of any organic agriculture practices; only one farmer who was aware of eco-friendly agriculture practices was encountered during my study, and to enrich his knowledge, he visited the nearest state, Jharkhand. Honey bees were identified from the photo album by almost every respondent (Fig. 4.21). Still, wild bees were identified by less than 50% of the respondents from each economic class except the farmer class. Some wild bees' like- *Xylocopa fenestrata*, *Xylocopa aestuans*, *Ceratina smaragdula*, *Amegilla zonata*, and *Megachile lanata* were identified by 56% of the farmer's respondents. *Xylocopa fenestrata* was the most popularly known wild bee.

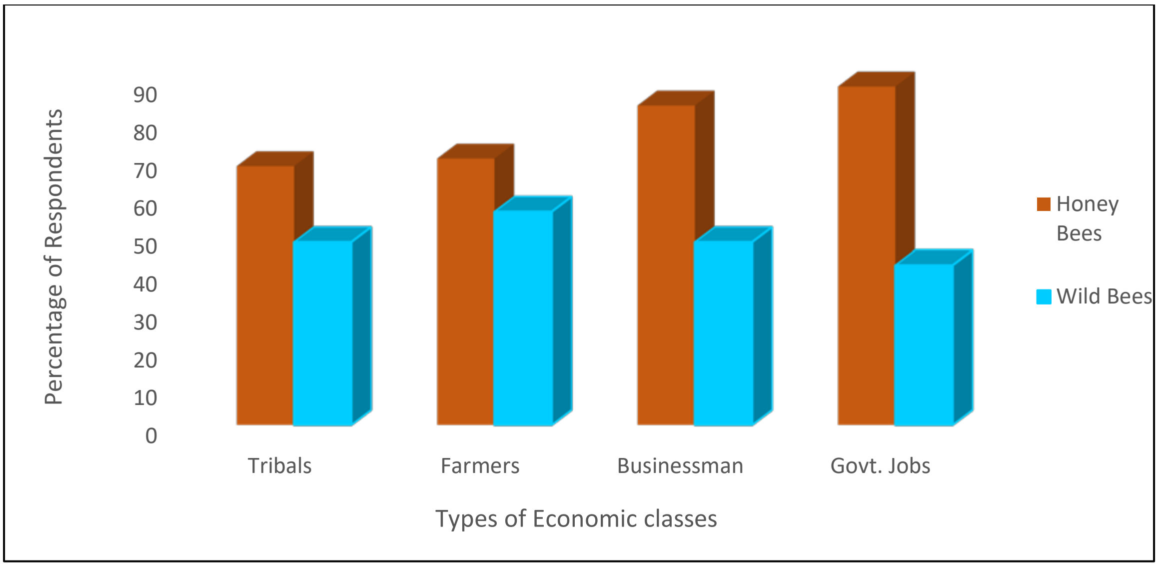


Fig. 4.21. Percentage of respondents among different economic classes identified honey bees and wild bees from the prepared bee album during the survey in KSFD.

4.6. Discussion

4.6.1. Species diversity pattern within the KSFD

At present, over 20,000 bee species are described worldwide. The majority of bee species are solitary bee species. However, solitary bees are the least studied. Honey bees gained greater attention and are the most studied, mainly due to their pollination service and economic importance.

In the present study in the KSFD, 25 species were documented from three habitats: mixed forest, Sal forest, and agricultural landscape. 96.3% of bee species in KSFD were successfully documented through total sampling. Bee species of 3 families- Apidae, Halictidae, and Megachilidae were recorded. The family Apidae encompassed the most abundant bee species in the study area, and Megachilidae encompassed the least abundant bee species. The most diverse and richer ecosystem for bee species emerged as the agricultural landscape; not only was bee species' abundance distributed in high evenness, but mixed forests had a low bee diversity and low evenness in the species distribution. Different plant species are comprised within mixed forests, each possessing different floral patterns and flowering periods, which can be reasons for the low level of evenness or imbalance in bee species distribution. In Sal forest, the evenness of bee species distribution was moderate, indicating a moderate attempt to maintain a balance in the species distribution within the ecosystem.

In the agricultural landscape, a diverse community of bee species interacting with crops was still signified by the relatively high value of the Shannon diversity index. A richer and more diverse community of bee species in crops like sunflower and sesame was implied by a relatively moderate Shannon diversity index value. A high diversity index value, which denotes a rich and diverse population of bee species interacting within these crops, was observed in crops like- green gram, ridge gourd, eggplant, and tomato. The pollination of the crops and the overall health and resilience of the ecosystems could benefit from the level of diversity, as unique contributions are made by different bee species, including incredibly solitary and native bees. Moderate variations in the abundance or occurrence of other species within these specific crops were suggested by Moderate Simpson evenness values. An attempt was made to maintain a relatively stable and diverse community within these crops, even though some species could be dominant over others. The fairly even distribution of different bee species within those crops was implied by the high value of evenness. A stable ecosystem for bee species within those crop fields, potentially contributing to effective pollination, could be signified by this balance in species abundance.

4.6.2. Similarity in compositions of bee communities across habitats

A significant difference between species composition or abundance was indicated by dissimilarity values in agricultural land and mixed forest; this suggested that these two habitats have distinct ecological characteristics that significantly differentiate one another. Similarly, substantial dissimilarity with agricultural land was exhibited by Sal forest. Even more significant was observed in the value when contrasting it with mixed forest. Agriculture areas had a different mix of crops and heterogeneous biodiversity compared to the natural ecosystem of mixed forest and Sal forest. Moderate levels of dissimilarity were exhibited by both the forest types (mixed and Sal forest). Sal forests are dominated by Sal trees (*Shorea robusta*), which differs from mixed forests. Still, similarities in ecological elements (like some common species), environmental characteristics, and ecosystem functions were shared by them.

Very high bee diversity and abundance were observed in the agricultural landscapes; likewise, there was a relatively high dissimilarity of bee composition between most crops (58.4%), a moderate level of unlikeness was observed in 33.4%, and a low level of difference was displayed in 8.2%. A profound difference in species composition or shared limited bee species was indicated by a 58.4% high degree of dissimilarity between crops due to their notable heterogeneity in growth patterns, ecological requirements, floral patterns, genetic compositions, or other factors. A high degree of difference in bee composition with all crops was maintained by tomato and eggplant, indicating a notable distinct dissimilarity or sharing very few similarities. A moderate level of dissimilarity (33.4%) within crops also suggested that a low to moderate portion of the bee species found in the agriculture landscape were shared among these crops. A shallow level of dissimilarity of bee composition between crops was observed among mustard-sunflower (0.305), green gram-sunflower (0.325), and cucumber-sesame (0.384). These crops implied that higher levels of similar bee species were attracted or supported for pollination or resource sharing.

4.6.3. Influence of Meteorological parameters on the abundance of Bees

A linear regression model was run on the data to demonstrate the significant influence of meteorological parameters like temperature, humidity, wind speed, and sky conditions on the abundance of bees. A positive correlation was observed between temperature (Dorjay et al., 2017), humidity (Prasifka et al., 2023), and abundance of bees. However, bee abundance was negatively correlated with wind speed and sky conditions. The increase in the abundance of bees was indicated by increasing average temperature and humidity. The abundance of bees was inversely influenced by wind speed and sky conditions.

4.6.4. Socio-economic survey

The majority of the residents in the study area were identified to be below the poverty level, according to the results of the present study. A low population density was observed in the Manbazar and Bandwan areas of the Purulia district (Ghosh, 2009), and it is noted that these areas were more predominantly comprised of Indigenous communities than other parts of the district (Kar et al., 2022). In Purulia, 994 villages were identified as “backward villages” based on inadequate employment and significantly low women’s literacy rates (Kar et al., 2022; Mahato, 2012). LPG couldn’t be afforded by the people living at the poverty level; hence, they depended on forest timber products and procured firewood from their nearest forest patches. Forests, whether as fuel wood or NTFPs, were strongly relied upon by the residents. Benefiting from the NTFPs was also observed among the people, as it constituted one of their sources of income. Mahua is a dominant flora popularly collected as flowers in the study sites. Accumulating Sal leaves and fruits was another popular activity as Sal leaves were sold to manufacture biodegradable utensils. Even cattle pasture was an everyday activity within the forest, prominently noticeable.

Dependency on agriculture practice as an earning source was high, and the tendency of migrant labor in the present generation was quite noticeable, as there are no options for other employment, high agricultural activity with low investment, and this type of dependency leads to land degradation in this region (Mahala, 2016). Agriculture practice was not considered eco-friendly; excessive pesticides were used, except mustard, green gram, and pigeon pea. Agriculture practices mainly occurred on land equal to or less than 3 acres due to the higher number of small-scale farmers. Awareness of bees among villagers was limited to honey and stingless bees. Less than 50% of the respondents were familiar with a few wild bees.

A moderate diversity of bee species was suggested by the findings observed across the study area, with 21 wild bee species being documented. The residents of the study area were highly dependent on agriculture practices due to fewer options for economic sources, which was positively reflected in the socio-economic survey. Bee species diversity and population were threatened due to the gradually increasing intensity of agriculture practices. It is crucial to conserve wild plant diversity in and around farmlands and complexity in crop cultivation to support wild bee diversity (Grass et al., 2016). The low diversity and low evenness in the mixed forests were highlighted by the study, indicating the requirement for proper management planning.

Plate- 6

Socio economic survey

Ecofriendly agriculture practice

Plate- 7
Anthropogenic activities




Chapter 5

Ecosystem services of wild bees in the agro ecosystem in contrast with anthropogenic activities

5.1. Introduction

Crop pollination by bees is an ecosystem service of immeasurable value, but now it is under rising threat from agricultural intensification. Crop pollination was an ecosystem service central to human welfare; its economic value was enormous despite being difficult to estimate precisely (Costanza et al., 1997; Heal, 2000). 35% of the world's crop production was dependent on pollination, and it was associated with a significant market value (IPBES, 2016). Various crops were effectively pollinated by native bees along with the *Apis* bees. Stabilization of pollination services over time against declines of any particular bee species was achieved through the accumulation of pollination services provided by wild bees and *Apis* bees (McCann, 2000; Kremen et al., 2002; Ricketts, 2004). Past studies have shown that the diversity and abundance of bees in the agricultural landscape decline significantly with increasing distance from natural habitat; this decline also differs among different taxa of bees (Ricketts et al., 2001; Perfecto & Vandermeer, 2002; Luck & Daily, 2003).

Pollination is an important regulating ecosystem, particularly in a diverse ecosystem like agroforestry, where wildflowers and crops are inevitable (Allen-Wardell et al., 1998). An intensive land management system known as Agroforestry is defined as agriculture that incorporates trees. The diverse range of ecosystem services was enhanced by this system, which bridges forestry and agriculture (Shin et al., 2020) and accommodates a diverse range of bee nesting and foraging sites. The agricultural landscape benefitted from pollinator abundance, while accelerated declines were also experienced due to land use change (De Marco and Coelho, 2004; Dicks et al., 2016). Lower resilience was observed in bees within agroecosystems, primarily due to their susceptibility to pesticides (Theodorou et al., 2020). The strengthening of ecosystem services by many bees was valuable, especially when considering multiple locations and services (Isbell et al., 2011). In the present investigation, the ecosystem services or pollination services of bees was studied throughout the KSFD in contrast to anthropogenic activities like - population density, electric power infrastructure, pasture lands, roads, railways, and navigable waterways on a weighted average variable that depicts human pressure on the environment.

5.2. Methodology

Bees were sampled along a belt transect (Fig. 3.1), 10 mins focal observation, and colored pan traps in the different agriculture fields, which was described in details in Chapter-3 (3.8). The experimental study was conducted in seven plots of agricultural land for every of nine crops. I sampled 63 agriculture sites (9 crops× 7 sites) and selected the peak flowering period to collect data and avoid unbiased data as it is when a maximum number of bees are active. Collected bees were preserved in 70% alcohol, and later, dry preservation was done in an insect box (Gullan & Cranston, 2005). Bees were identified by identification key by Bingham (1897) and Michener (1974, 1994, 2007). The exact location of the study sites was recorded using GPS (Global Positioning System).

5.3. Data Analysis

5.3.1. Species diversity

The bee species abundance data in each crop pooled independently and inserted in Microsoft office Excel 2016 software for analysis diversity by Shannon diversity index (H’).

Shannon Diversity Index $(H') = -\Sigma p_i * ln(p_i)$

Where, S is the total number of species and p_i is the proportion of the entire community made up of species i.

5.3.2. Interpolation (IDW) analysis

Geographic Information System (GIS) or geographic (or geographical) information science was operated first in the 1950s in North America, mostly with maps automated production. Geographic Information is represented by a series of geographic datasets that let the model geography utilize simple and generic data structures. Comprehensive tools to work with geographic data is included in GIS and helps develop and analyze spatially explicit variables. GIS techniques have been widely utilized in forestry, ecology, agriculture, environmental management, remote sensing, mining, and geosciences. Arc-GIS is a Desktop Product for creating, importing, editing, querying, mapping, analyzing, and publishing Geographic Information.

Interpolation is utilizing known data values for estimating unknown data values. Interpolation can predict values of cells in a raster of a limited account of sample data points. It may be utilized to predict unknown values of geographic point data like elevation, rainfall, population density, etc. Spatial interpolation is the method of estimating the values of properties at non-sampled sites within an area covered by existing observations. The estimations of all Spatial Interpolation techniques may be presented as weighted averages of the sampled data and create a raster surface with estimates for all raster cells. Among many interpolation methods, inverse distance weighting (IDW) and triangulated irregular network (TIN) are the two most widely used. They all have a share of the general estimation formula, as follows:

$$\hat{z}(x_0) = \Sigma^{n}_{i=1} \lambda i z\ (x_i)$$

Where zˆ represents the estimating value of an attribute at the location of interest point xi, z represents the observing value at the sampled point x_i, λ_i represents the weight assigned for the sampled point, and n is the number of sampled points utilized of the estimation. So, the attribute is usually known as the primary variable (especially in the geostatistics field).

Inverse Distance Weighted (IDW) interpolation analysis was engaged to prepare raster maps. The fundamental concept beyond IDW is that points close to each other in space tend to have the same attribute values. IDW Interpolation implements a fundamental law, Tobler's First Law of Geography: "Everything is related to everything else, but near things are more related than distant things." The known surrounding values of the estimation location were utilized by IDW to estimate the value of any unknown location. The more substantial influence on the assessed value was measured by these values (closest to the estimation location) than those that are not closest (for this rezone, it is known as inverse distance weighted). Predicting the height of the unknown points was dependent on this method by computing the distances between the measured points and the other known points. It is mathematically represented as follows:

$$z(x,y) = \frac{\sum_{i=1}^{n}\left[\frac{z_i}{d_i^p}\right]}{\sum_{i=1}^{n}\left[\frac{1}{d_i^p}\right]}$$

$$z\ (x,y) = \sum \lambda_i \times z_i \underline{Where} \sum \lambda_i = 1$$

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}$$

Where z (x, y) represents the estimated value at the unmeasured location (x, y); i represents the number of sample points in the defining neighborhood; z and the known location i; λi is the distance dependent weight associated with each known point; and p represents the power parameter that is define the rate reduction in the weight as the distance increasing.

Where z (x, y) represents the estimated value at the unmeasured location (x, y); i represents the number of sample points in the defining neighbourhood; z and the known location i; λi is the distance-dependent weight associated with each available point; and p represents the power parameter that defines the rate reduction in the weight as the distance increasing.

For better evaluation, the interpolated Shannon diversity index of social bees (Fig. 5.2) and wild bees were generated separately (Fig 5.3) to understand the current scenario of their diversity and their probability of ecosystem services. Social bees are those bee species involved in living in communal nesting. Five social bee species, *Apis dorsata*, *Apis cerana*, *Apis florea*, and *Tetragonula iridipennis* were documented in my study area (Thomas et al., 2009). The diversity data of each bee species for interpolation was pooled together.

5.3.3. Human Footprint Index

The disruption of pollination as a diffuse ecological function (Aguilar & Galetto, 2004; Aguilar et al., 2006) and service (Ricketts et al., 2008; Gibbs et al., 2016; Garibaldi et al., 2016) is directly associated with human-modified landscape. In human-modified landscapes, populations of both pollinators and flowering plants, mainly those with specialized reproductive traits, are frequently driven to local extinction or reduced (Girão et al., 2007; Lopes et al., 2009; Tabarelli et al., 2010). Moreover, the flow of pollen among populations is further reduced by the geographic isolations of populations in forest remnants with hyper fragmented landscapes, thereby limiting plant reproductive success (Ricketts et al., 2004; Ricketts et al., 2008; Llorens et al., 2012). Analysis of anthropogenic pressure is needed, to understand the reflection of real socioeconomic costs of environmental degradation (Radford & James, 2013). Human impacts of the study area was analyzed through the Human Footprint Index (HFI) map. The study area (KSFD) was extracted from the world HFI map.

The cumulative pressure of human influences on the environment could be assessed with the Human Footprint Index or HFI (Venter et al., 2016). HFI maps of 2009, with a resolution of 1 km^2 were included in the GeoTiffs. The calculated HFI map was downloaded from the SEDAC (Socio-Economic Data Application Center). The influences of various human pressures were summarized by the HFI. Human pressure or activities were measured using eight variables, including built-up environments, population density, crop lands, pasture lands, electric power infrastructure, roads, railways, and navigable waterways, on a weighted average variable that depicts human pressure on the environment. Remote sensing and observational quantification of human impacts were integrated and represents the most recent and comprehensive information available for large-scale ecological studies. The map was downloaded from SEDAC into the ArcGIS (10.6.1). The coordination of the study locations was positioned depending on their geographic coordinates.

The average HFI of the study area was classified into eight categories, considering index values ranging from 8- 26. Venter et al. (2016) and Di Marco et al. (2018) signified the "wilderness human area" by the HFI value "zero," and a very high human pressure level (e.g., a densely populated area) was represented by a value above "20". Based on the above information, five classes of HFI values were assigned: as-Negligible (HFI- 8-10.25); Very Low (HFI- 10-12.51); Low (HFI -12.51-15); slightly intermediate (HFI- 15-17); Intermediate (HFI- 17- 19.3); highly intermediate (HFI-19.3-21.5); High (HFI-21.5-23.9); Very high (HFI- 23.9-26).

5.4. Results

5.4.1. Interpolated diversity of bees

In the study areas, extensively diversity in bee species (1.7 – 2.3) was observed at sites 27, 29, 35, 43, 46, 48, 53, 56, and 59 through interpolation (Fig. 5.1). The rate of pollination services was increased by the high diversity observed at these sites. Bee diversity values between 1.5 - 1.7 were found in twelve study sites 3, 10, 22, 28, 32, 36, 47, 49, 58, and 62. Sharp decreases in bee diversity index were observed in fifteen study sites 1, 4, 8, 9, 11, 12, 13, 14, 15, 30, 38, 40, 42, 51, 52, and 63, ranging from 0.54922 - 1.2435, indicating low pollination services. Moderately diverse bee species (1.4 – 1.5) areas covered 28.57% of the total study area, including sites 2, 5, 7, 17, 19, 23, 24, 33, 41, 44, 50, 54, and 55. Slightly moderate bee species diversity, with a Shannon diversity index of 1.2 to 1.4, was exhibited in sites 21, 25, 26, 34, 39, and 61.

5.4.2. Interpolated diversity of social bees

Comparatively higher interpolated diversity of social bees (Fig. 5.2), ranging from (1.11- 1.3873) was shown in sites 26, 28, 43, 46, 47, and 48. Relatively moderate diversity of social bees was observed in sixteen locations Sites- 2, 6, 7, 10, 12, 19, 21, 23, 24, 30, 36, 37, 39, 41, 45, and 49. Most of the study area displayed a less moderate diversity index of social bees (0.55496- 0.8324). Less diverse values, ranging from 0.27752- 0.55495, were found in sites 3, 8, 14, 40, and 52. Negligible diversity of the social bees was shown in the rest of the locations.

5.4.3. Interpolated diversity of Wild Bees

The diversity of wild bees (Fig. 5.3) was considerably higher than that of the social bees in the study area. Sites 51, 53, and 59 show very high diversity, ranging from 1.8 to 2.2. Most of the part of the study sites exhibit moderate diversity (0.9- 1.4), whereas some sites, like- 7, 23, 25, 27, 34, 35, 36, 37, 39, 41, 43, 46, 55, 58, 60 and 61 displayed high level of diversity (1.363- 1.805). Few sites showed negligible wild bee diversity (1, 3, 4, 5, 18, 24, 29, and 42). Low diversity ranged from 0.47- 0.91 in sites – 2, 3, 9, 12, 13, 14, 17, 29, 44, 45, 47, and 58.

5.4.4 Description of degree of anthropogenic pressure

The majority of the study area had a low HFI value (Fig. 5.4). Negligible HFI values were noticed in study sites 2, 13, 30, 32, 33, and 51. Slightly Intermediate HFI value was observed in sites 1, 10, 15, 19, 25, 39, 40, 46, 47, 53, 54, and 59. Four sites – 25, 50, 59, and 60 were surveyed in intermediate HFI. Highly intermediate HFI values were found in sites 3, 38, and 58. Whereas studied sites 8, 17, 36, 43, 46, 47, 55, and 56 were situated at high HFI value zones, only two surveyed sites, 13 and 52, were located in high HFI zones. I did not survey any sites near low HFI zones.

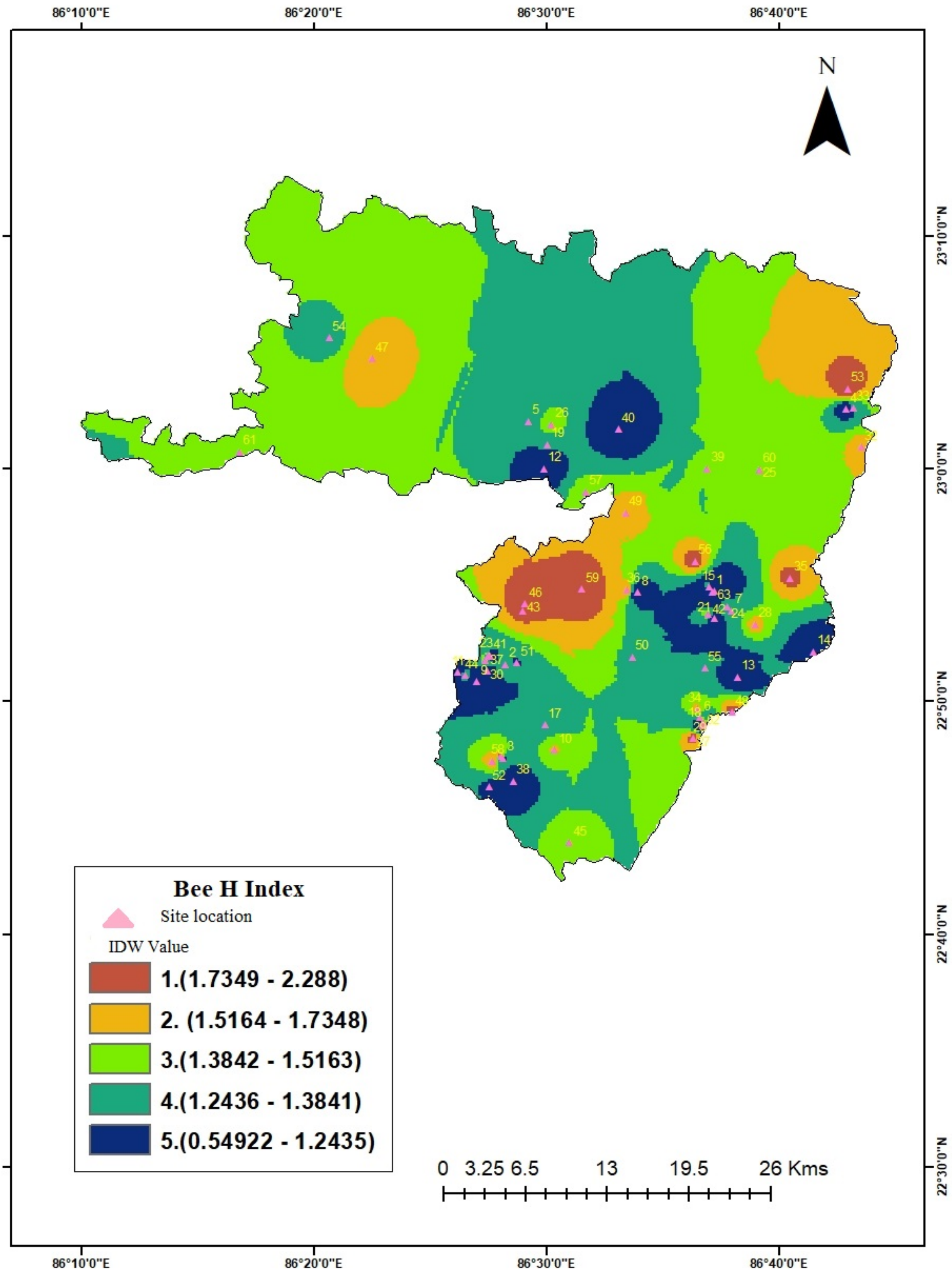


Fig. 5.1. Pooled bee species diversity predicted the spatial map generated by Inverse Distance Weighting (IDW).

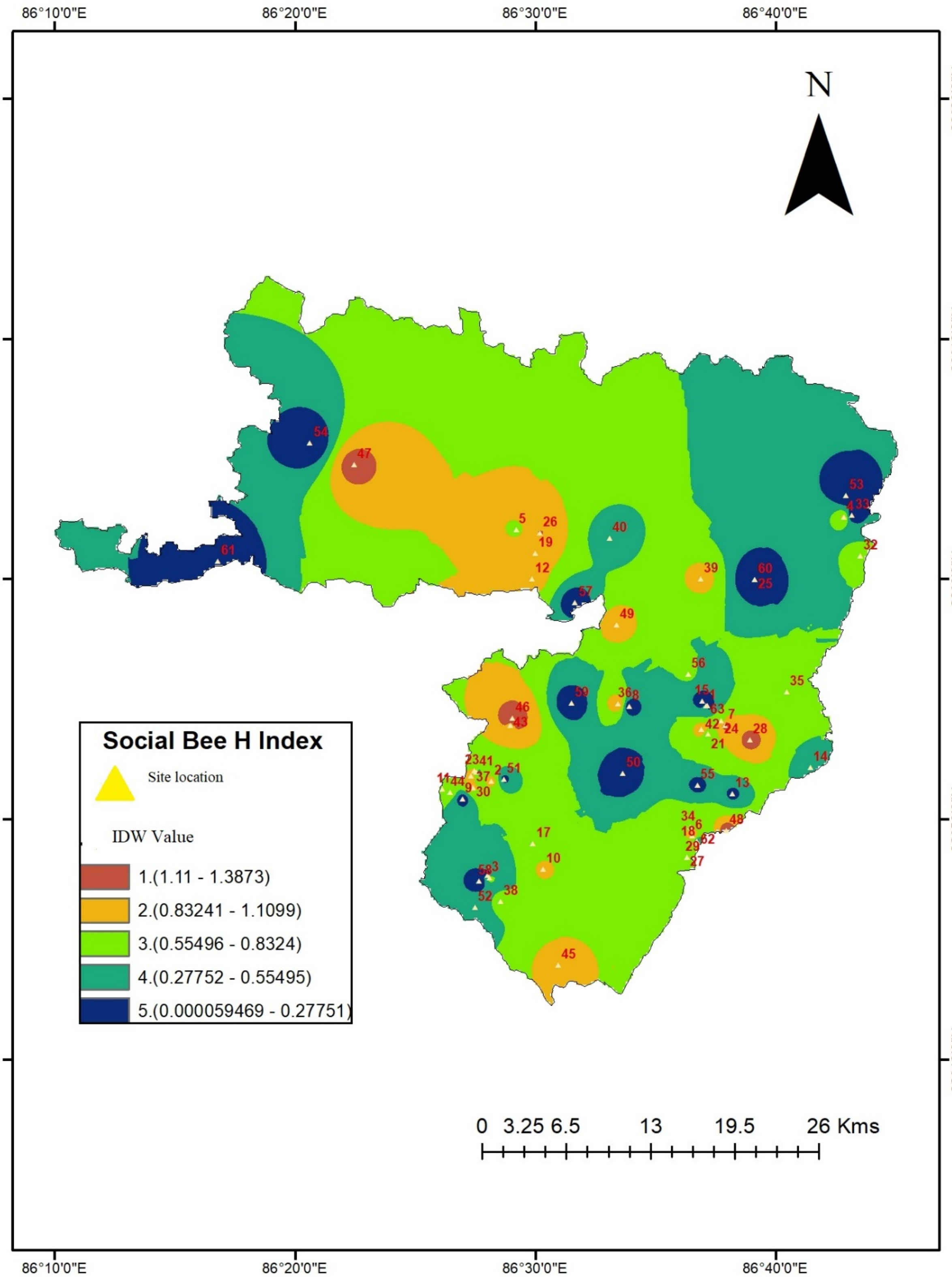


Fig. 5.2. Social bee species diversity predicted the spatial map generated by Inverse Distance Weighting (IDW).

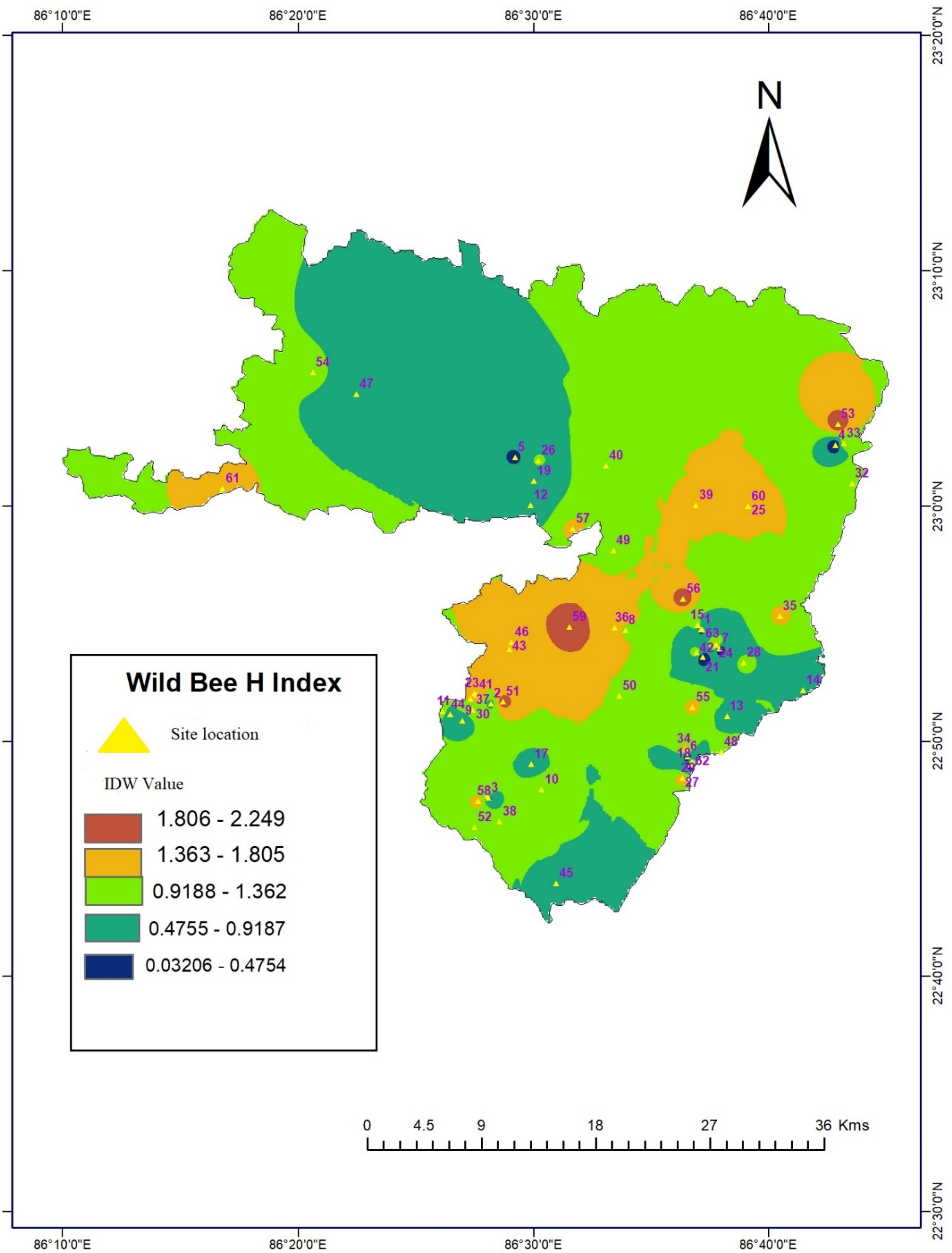


Fig. 5.3. Wild bee species diversity predicted the spatial map generated by Inverse Distance Weighting (IDW).

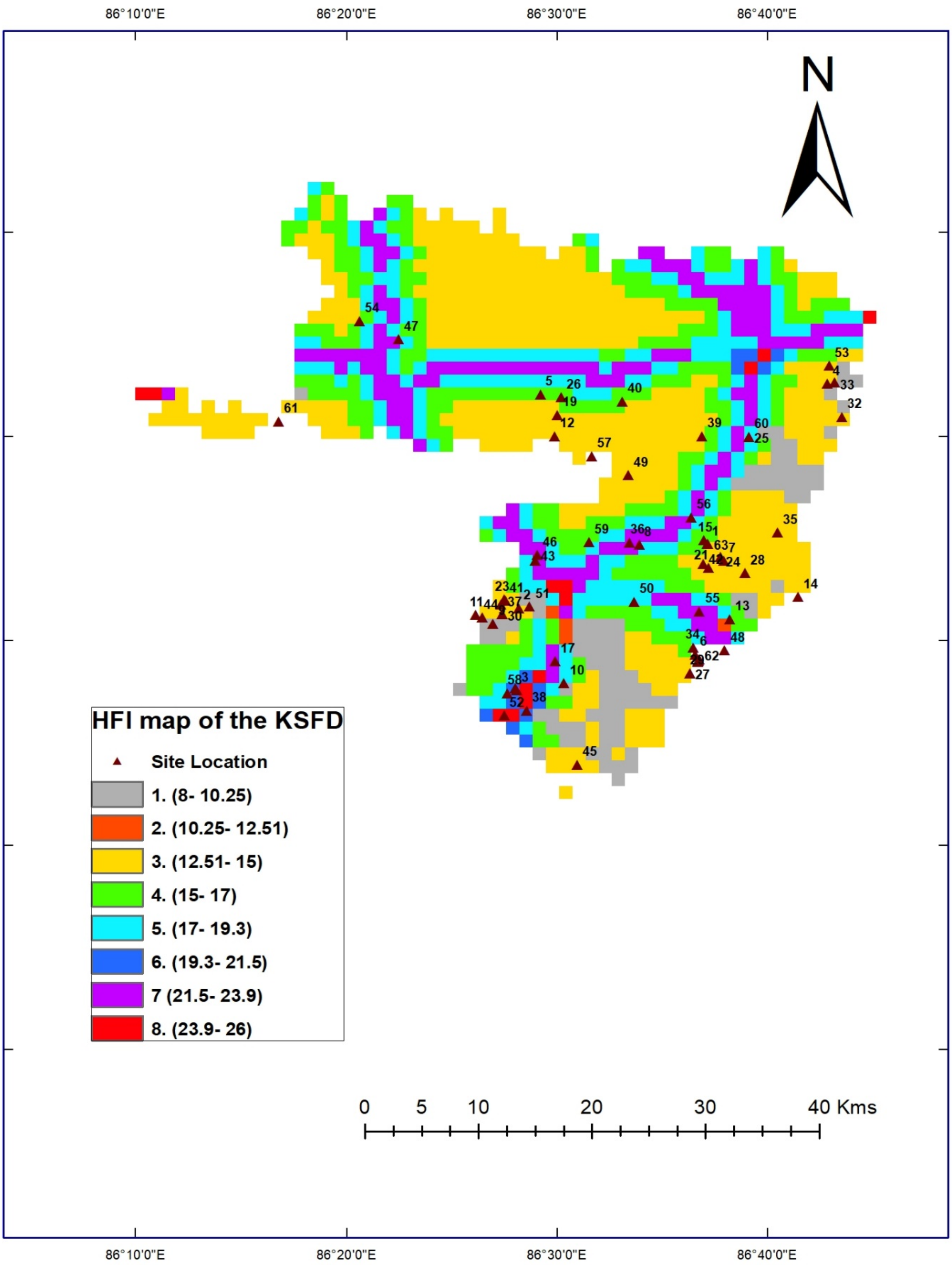


Fig. 5.4. Human Footprint Index (HFI) map of KSFD.

5.5. Discussion

A positive association between bee species diversity and stability in ecosystem services has been observed in various theoretical and empirical studies (Lehman & Tilman, 2000; Balvanera et al., 2006; Garibaldi et al., 2011). The ecosystem services of bee communities were studied on base bee species diversity in each location, and their spatial distribution is computed by interpolation (IDW). For further understanding, the bee community was differentiated into social and wild bees. Hence, interpolated maps were generated for social bee and wild bee distribution separately based on their diversity indexes in each surveyed site. The HFI map of KSFD was extracted from the HFI map 2009 (Venter et al., 2016) and classified into eight categories to interpret anthropogenic activity in KSFD better.

5.5.1. Interpolated diversity of bees species

Moderate diversity of the bee community was observed. The diversity of the wild bee was relatively high, whereas the diversity of social bees is relatively low. High bee diversity was cumulatively observed in sites 43, 46, and 59, especially for social and wild bees. However, in most cases, the results were contradictory.

Cumulative moderate bee diversity was observed in sites 47 and 49, but this site was highly diverse for social bees and poor diversity for wild bees. In some studied locations (sites- 12, 19, 26, and 45), a high diversity of the social bees was noticed, but surprisingly, wild and pooled bee diversity was shallow. A similar trend was also recognized in sites 25, 57, 60, and 61; the diversity of wild bees was relatively high, but negligible diversity of social bees was observed, and the result of pooled diversity was moderate. In site 40, the diversity of wild bees and cumulative bee communities was moderately distributed, but surprisingly, the social bee diversity index was low. In many sites, like 1, 9, 13, 15, 38, and 52; the diversity index value of wild bees was higher than pooled and social bee diversity values. The interpolated map indicated that the wild bees' diversity was moderate and spatially distributed throughout the study area. A negative correlation in the diversity distribution between social bees and wild bees was observed in sites – 5, 12, 19, 25, 26, 45, 47, 51, 53, 55, 57, 58, 59, 60, and 61.

5.5.2. Description of degree of anthropogenic pressure

The HFI value of KSFD was expressed as low to slightly intermediate anthropogenic impact throughout the studied area. These areas mainly feature agricultural land, which demonstrates the conversion of forest landscape to agricultural land; the trend of the altered landscape was dominantly observed. The negligible value of HFI was explained by the forest patches of the area. Pollinator abundance is profited from agriculture landscape and also is primarily driven to decline the population through land-use change, agro-chemical and large-scale farming practices (De Marco & Coelho, 2004; Dicks et al., 2016, Porto et al., 2020).

Very high HFI value zones were also observed in the surveyed area, and study sites like- 52, 38, 58, and 13 were in those zones; they showed negligible bee diversity for social and wild bees. Moderate to highly moderate bee diversity was still exhibited in the high HFI zone (sites 17, 36, 8, 56, 55, 46, 43, and 47). Slightly low diversity zones of bee species were displayed in the surveyed locations in the slightly intermediate zones to highly intermediate zones (sites 10, 50, 34, 6, 59, 15, 1, 60, 25, 40, 19, 26, 5, and 54). In contrary, few sites shown moderate diversity of social bees observed in 10, 5, 19, and 26 and high diversity index of wild bees observed in 34, 59, 60, and 25 in spite of intermediate anthropogenic pressure. A very high wild bee diversity index was demonstrated in sites 4, 33, and 53 near negligible HFI zones.

Higher bee diversities were noticed in the agricultural landscapes near natural habitats, and bee diversity gradually declined with the increasing distance from the natural habitat (Virkar, 2017). In the investigation, natural habitat with negligible HFI values was observed in very few sites, and a slightly intermediate anthropogenic impact was evident across the study area, demonstrating a noticeable habit alteration process. This fact was also certified by the socio-economic survey in Chapter 4 (4.5.4). The decline of bee species and the intensity of their ecosystem services were prominently threatened by changes in land-use land cover. It was suggested by this study that bee diversity, as well as their ecosystem services, were slightly affected by ongoing anthropogenic activities.

Chapter - 6

Role of non- crops in sustaining pollen network

6.1. Introduction

The relationship between pollinators and plants is a co-evolutionary mutualistic relationship. Flowers and bees have the best mutualistic relationship for ecological and nutritional aspects (Sakagami et al., 1967). Ecological interaction networks are representations of associations between species. Bees were directly involved in maintaining native plant diversity through pollination; those plants depend on bees for guaranteed reproduction success (Ollerton et al., 2011). Past investigations revealed that plant-pollinator network structures were a better projection of pollination services than the species diversity alone; unique and high linkage diversity contribute more excellent and stable pollination services than those with low linkage diversity (Elle et al., 2012; Tylianakis et al., 2010).

Changes in land use due to anthropogenic activities lead to fragmentation and habitat loss, which tend to have reduced plant and pollinator diversity and abundance (Krauss et al., 2009; Neame et al., 2013). Mutualistic interactions like plant-pollinator networks were formed of central species connected to numerous peripheral species. If the central species were extinct, all dependent species would follow the same path, with subsequent cascading impacts in the community (Memmott et al., 2005). Heterospecific pollen transfer (HPT) in natural communities helps to overcome that undesirable scenario, but it remains largely unexplored. Bidirectional HPT occurs when different species share the same pollinator, sparsely observed in the species-rich community (Fang & Huang, 2013). In the present investigation, I studied the plant-pollinator network throughout the KSFD and the role of numerous non-crop plants in maintaining this network, implicating their role in crop production by conserving the bee community.

6.2. Data for plant-pollinator interaction studies

The research on the future of declining pollinators and its effects on plant reproduction and fruit yields should be approached with mutualistic interaction with attention to the "species functional groups" by researchers (Geslin et al., 2013). It was foremost to conduct scientific investigations on a more functional level dealing with the traits of either pollinators or flowers. Bees respond to commonly found floral colors (Krik, 1994) and their pollen as a reward for pollination services (Leong & Thorp, 1999).

The experimental study of plant-bee interactions required methods either phytocentric (observing flowers for pollinator visitations) or zoocentric (recording interaction based on pollen loads acquired from bees captured using sweep nets or nests) (Bosch et al., 2009). However, the zoocentric method requires skilled collectors (Westphal et al., 2008), even if they only sample some of the scarce species and small bees, and locating nests for all bees takes time and effort. They could also miss out on rare ones (Jordano, 1987; Sorensen et al., 2011). A case study by Chacoff et al. (2012) exhibits that interaction data did not reach an asymptote after four years of study. Passive sampling methods like colored pan traps are preferable for long-term monitoring, as they represent the natural floral color, attracting diverse pollinators, chiefly bees. Numerous surveyors have used this method over the years, and it has provided reliable results (Westphal, 2008). In this investigation, I utilized both active (collecting bees and their pollen) and passive sampling (colored pan traps) to understand the plant-bee interactions at their functional levels based on the above evidence. The survey was conducted in non-crop plants near the crop fields and forest throughout the year, in different seasons, from February 2020 to April 2023 in KSFD.

6.2.1. Using Active Sampling Data

Collection of bees - Net sweeps used to collect bee foragers of non-crop plants for identification.

6.2.2. Using Colored Pantrap Sampling Data

Colored Pantraps was used as a passive sampling to avoid observer bias, and it could easily be used irrespective of surveyor experience. Also, they were offered the flexibility of primary colors found in nature; as an outcome, they were attracted to and could collect fairly diverse bee fauna, incredibly cryptic species (most native bees). Pantraps of three primary colors, yellow, white, and blue, predominantly found in nature was set for sampling. Pantraps were painted with a bright UV color. Five clusters of pan traps were established in a belt transect, where each cluster was separated by one another at a distance of 15m. Each sub-sampling pantrap (5×5 m) contained 15 pantraps of three different colors (Fig. 3.1). Hence, 75 pantraps were placed in each belt transect, and 1365 sets of pantraps (6825, three different colors of pantraps) were run across the KSFD. Pan traps were filled with clean tap water, and a drop of liquid soap solution was used to decrease the water's surface tension to drown the insects that landed. Pantrapped bees were washed with normal water and transferred to 70% alcohol-based vials until further identification.

6.2.3. Identification of specimen

A standard identification key by Bingham (1897) and Michener (1974, 1994, 2007) was followed for bee identification into families and morpho-species. Bee taxonomist Dr. Jagdish Saini identified species at the Department of Zoology, Allahabad University lab.

6.3. Data Analysis

Specimens were collected in colored pan traps, a number of flower visitors were observed, and data from prepared slides were pooled together and utilized to construct the bipartite networks between bees and plants in the study area. The three floral functional groups (color morphotypes) based on pantrap colors were yellow, blue, and white. Bee species were arranged with the respective colors in which they were found. An interaction network matrix was constructed. The pollination web had "m" rows depicting floral groups and "n" columns as bees. The interaction matrix is "A," and the value "Aij" was obtained as the intersection of the "ith" row with the "jth" column, which was represented by the interaction between floral functional groups and bees (floral functional group "i" to bee species "j"). The interaction matrices were developed using the R package bipartite 2.18 (R version 4.3.2). Bipartite network offers two main functions, plotweb and visweb; they produce network diagrams that were constructed in R software, "bipartite web" and "bipartite matrix," respectively (Dormann et al., 2008), from the bipartite package (Dormann et al., 2009). The weighted interaction frequency was incorporated into plots to display interactions proportional to the observed number of pollinators.

6.3.1. Computing Indices

Network indices were metrics to quantify an aspect of the network. Network indices were highly correlated as the information in a matrix is only finite. The Bipartite packages offered various indices; dozens of indices could be computed with one function, but some indices would significantly correlate with the requirement. Indices came at the following hierarchical levels- network- level, group-level, link-level, node-level, and species-level. For further investigation, species-level and link-level were chosen to follow. Species-level was used to compute indices for each species, and link-level was used to investigate the level of individual links or network matrix in the studied network for better understanding.

Species-level indices- The interactions were represented by a web matrix observed among higher trophic level species (columns) and lower trophic level (rows) species. These indices could be computed for each species in the network. A relatively comprehensive study of species-level indices led to specialization. Vectors of the calculated matrix were normalized degrees (ND), "species strength" as the sum of dependencies for each species, paired difference index (PDI), coefficient of variations of interactions (species specificity), pollination service index (PSI), node specialization index, betweenness, closeness, Fisher's Alpha index, Shannon diversity of interaction of that species, "effective partners" for the adequate number of interacting partners.

Link level indices- This indices had been investigated at the level of the individual link (i.e. the cell of a network matrix). Most studies at this level did not correct for the fact that observations per cell were clearly non-independent, or for the species abundances, which also significantly influence indices. Hence, it was employed by applying dependence one matrix for each level (the relevance of each species for the level, Bascompte et al., 2006) and endpoint degree (product of degrees of species linked by this cell, Barrat et al., 2004) to the network.

The HL (Host- Linked) dependence and LL (Linked) dependence were the vectors that needed to be calculated for these indices. The structural and functional aspects of the network were described by them, and the patterns of interactions and dependencies within the network were also analyzed. HL dependence signifies the relationship between one set of species (hosts) (e.g., Plants or animals) and another set of species that are "linked" to or dependent on the hosts. In the ecological network context, HL dependence was referred to as the interaction where hosts provide resources to other "linked" species. The relationship between species within the same set of species within a single trophic level or guild was represented by LL dependence. In ecological network aspects, LL dependence means interactions or dependencies among species of similar ecological roles.

6.3.2. Comparing the real network with null models

Null models were established to correct for statistical artifacts and to set an expectation without the hypothesized structuring mechanism. The results from a dynamic interaction between species at two levels were observed in real networks. The plant-pollinator network was influenced by nectar and pollen presence in flowers, plant growth, and plant nutrients. This interaction was also reflected by attractiveness between plant and pollinator, rather than an abundance of flowers or pollinators. Hence, null models were essential for understanding whether ecological or biological interactions are structured non-randomly, indicating the presence of ecological or evolutionary processes. Corrected indices and Z-score, the null model was applied for analysis as a single network studied. The null model would compute z-scores (standard scores or normal scores) for the network, which express the contrast in terms of standard deviations of the null distribution –

$$z_I = \frac{I_{\text{observed}} - \bar{I}_{\text{nulls}}}{\sigma_{I_{\text{nulls}}}}.$$

I compared accurate community responses with null models to compute the extent to which bee interactions with floral functional groups affect the pollen network in the study area, KSFD. There were various types of models used in the Bipartite network. I used the NODF (Nestedness Overlap and Decreasing Fill) null model here. The NODF null model was used to test for nestedness; it shuffles interactions while keeping row and column sums fixed to see if the observed nested pattern differs from the expected pattern.

The null model was run for 2000 iterations, and observed network structure values were compared with values obtained from null models (expected values- peak values obtained from randomizations).

6.4. Results

6.4.1. Pollination network in KSFD

I observed plant-pollinator interactions through direct observation and three floral functional groups based on pan trap colors in all forest areas of KSFD. I collected 8 bee species belonging to three families (Apidae, Halictidae, Megachilidae) from pan traps. *Lassioglossum* sp. had a dominant interaction (51%), and a minor interaction was observed in *Ceratina hieroglyphica* (1.3%) among all bee species that were collected from pantraps. Most bees preferred interacting with the yellow pan trap (50.32% of total interaction). I collected *Megachile hera* only white pan trap. A similar behavioral pattern was also noticed for *Nomia elliotii*, which was preferred only by the yellow pan trap. Bees interacted with white pan traps around 39.2%, and the least interacted with blue pan traps (10.5%).

In direct observation and slide preparation I encountered 8 bee species of three families (Apidae, Halictidae, Megachilidae). *Tetragonula iridipennis* was most actively interacted (59.12%) with all plants except *Terminalia tomentosa*. The contribution of *Apis dorsata* (22.98%) was also noticeable compared to other bee species. It was observed that *Megachile lanata* and *Amegilla zonata* had negligible interaction (0.69%). *Megachile lanata* was only noticed in *Butea monosperma*, whereas *Amegilla zonata* was observed in *Butea monosperma* and *Clerodendrum infortunatum*. The most widespread plant species in the study area were *Butea monosperma* and *Shorea robusta*. Wild bees only interacted with *Butea monosperma,* whereas *Apis* bees and *Tetragonula iridipennis* were shown to interact with *Shorea robusta* alongside.

In the Bipartite matrix, the interaction matrices consisting of the bee species were arranged in columns, and plant functional groups were organized in rows. The intensity of interaction was depicted with varying tints of black. Strong interactions were represented by darker tints and higher visitations by bees. Fewer interactions and fewer visitations were displayed by lighter tints among the mutualist species.

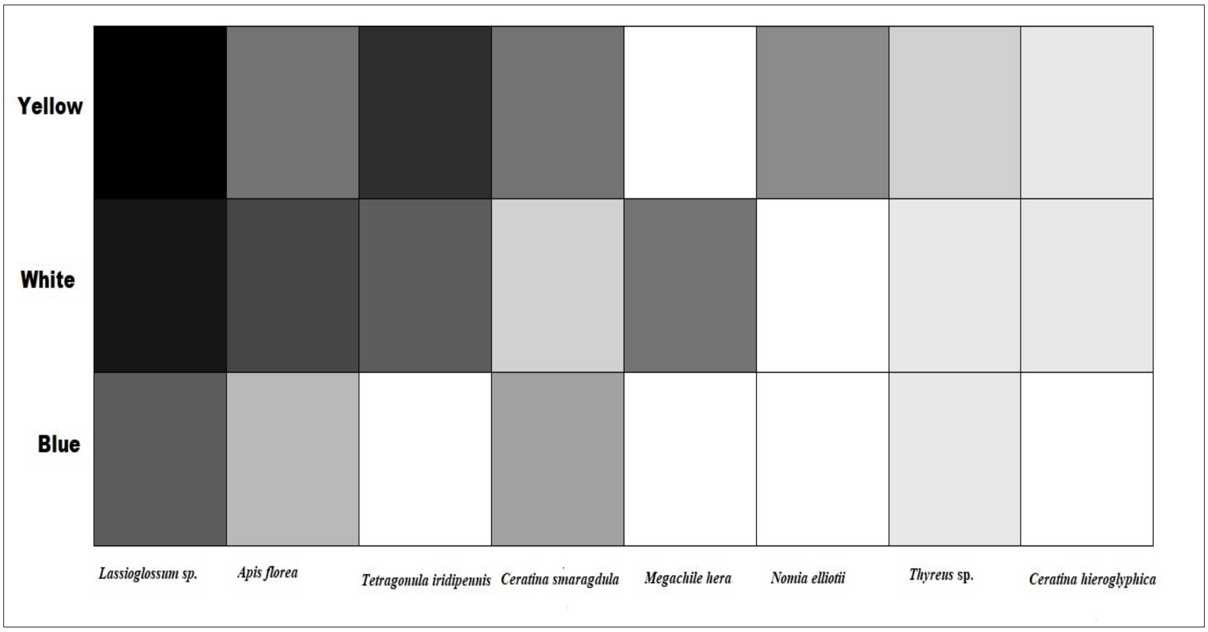


Fig. 6.1. Bipartite matrix showing the interaction between the bees and their floral functional groups (pantraps) in forest areas of KSFD. Vertical axis represents floral functional groups horizontal axis represents bees species. The intensity of interaction is depicted by varying tints of black, darker tints depict intense interactions and lighter tints display fewer interactions between species.

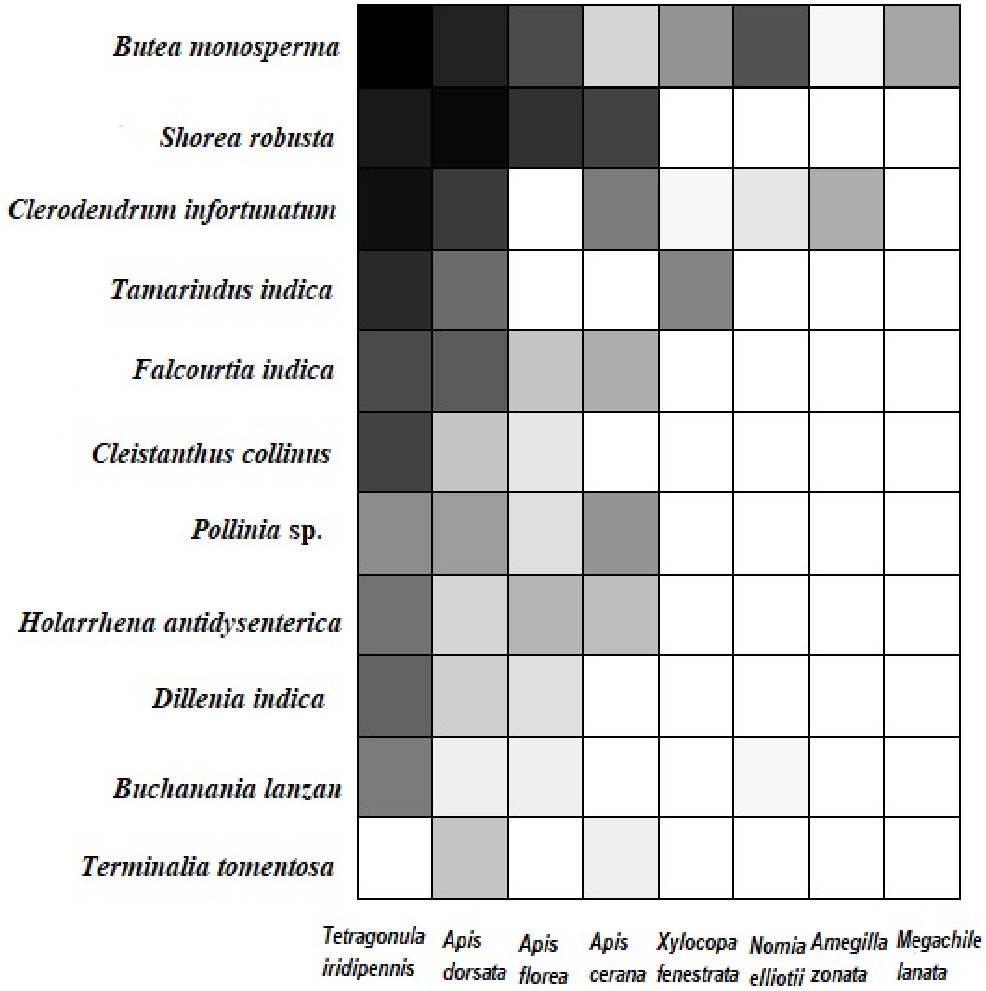


Fig. 6.2. Bipartite matrix showing the interaction between the bees and their interaction with the plants in forest areas of KSFD. Vertical axis represents plant species and horizontal axis represents bees species. The intensity of interaction is depicted by varying tints of black, darker tints depict intense interactions and lighter tints display fewer interactions between species.

The bipartite webs were based on the pollination matrix consisting of bee species, plant functional groups, and plant species. The bee species were arranged above the plant functional groups and plant species for the bipartite webs. The interactions between bees and plants were shown as "wheat" colored links; based on the number of interactions between plants and bees, the thickness of the links varies.

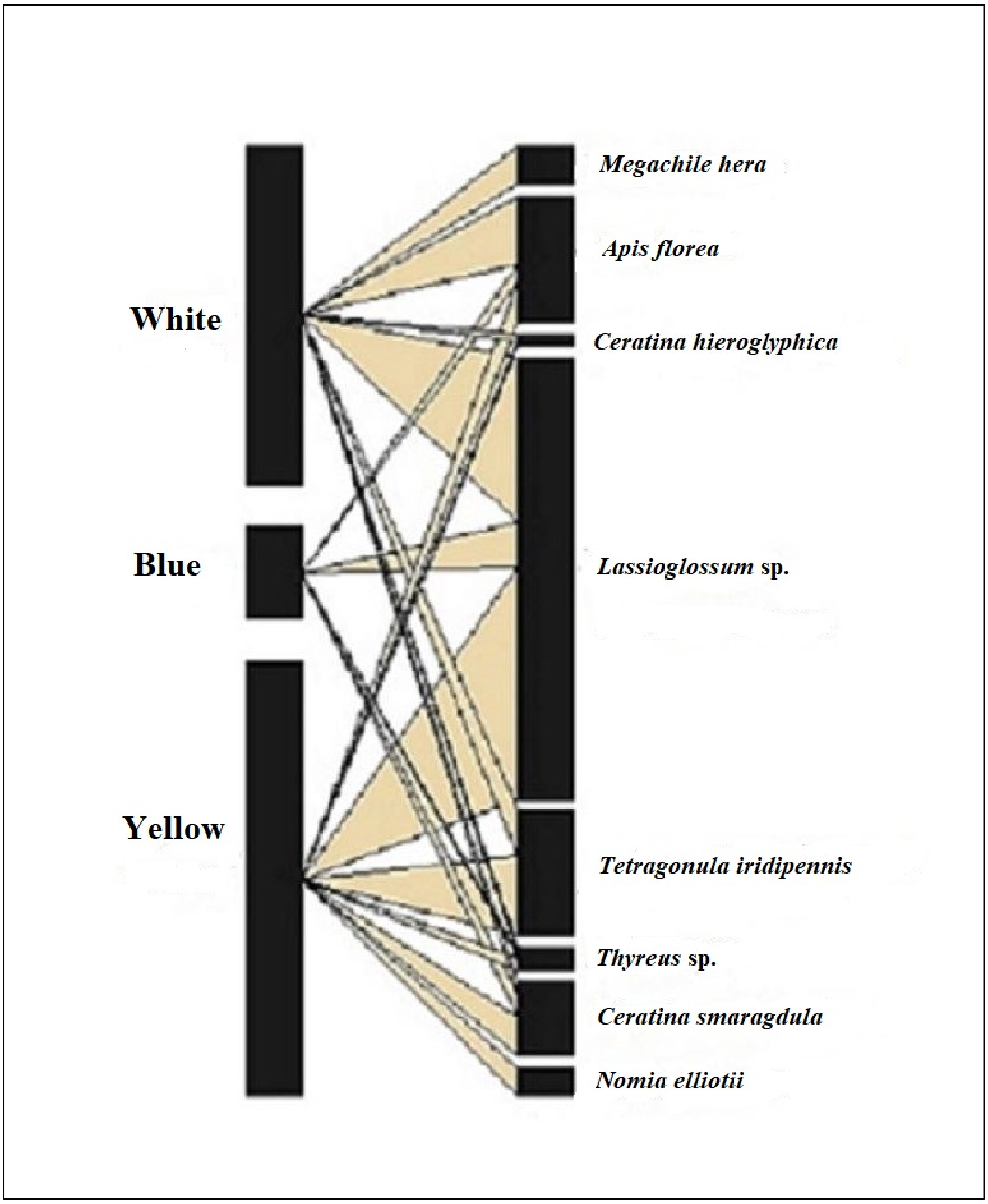


Fig. 6.3. Bipartite web showing the interaction between the bees and their functional floral groups in forest areas of KSFD. The boxes on the left are the floral functional groups and boxes on the right represent the bees species. The lines connecting floral functional groups and bees are the interaction events weighted by abundance.

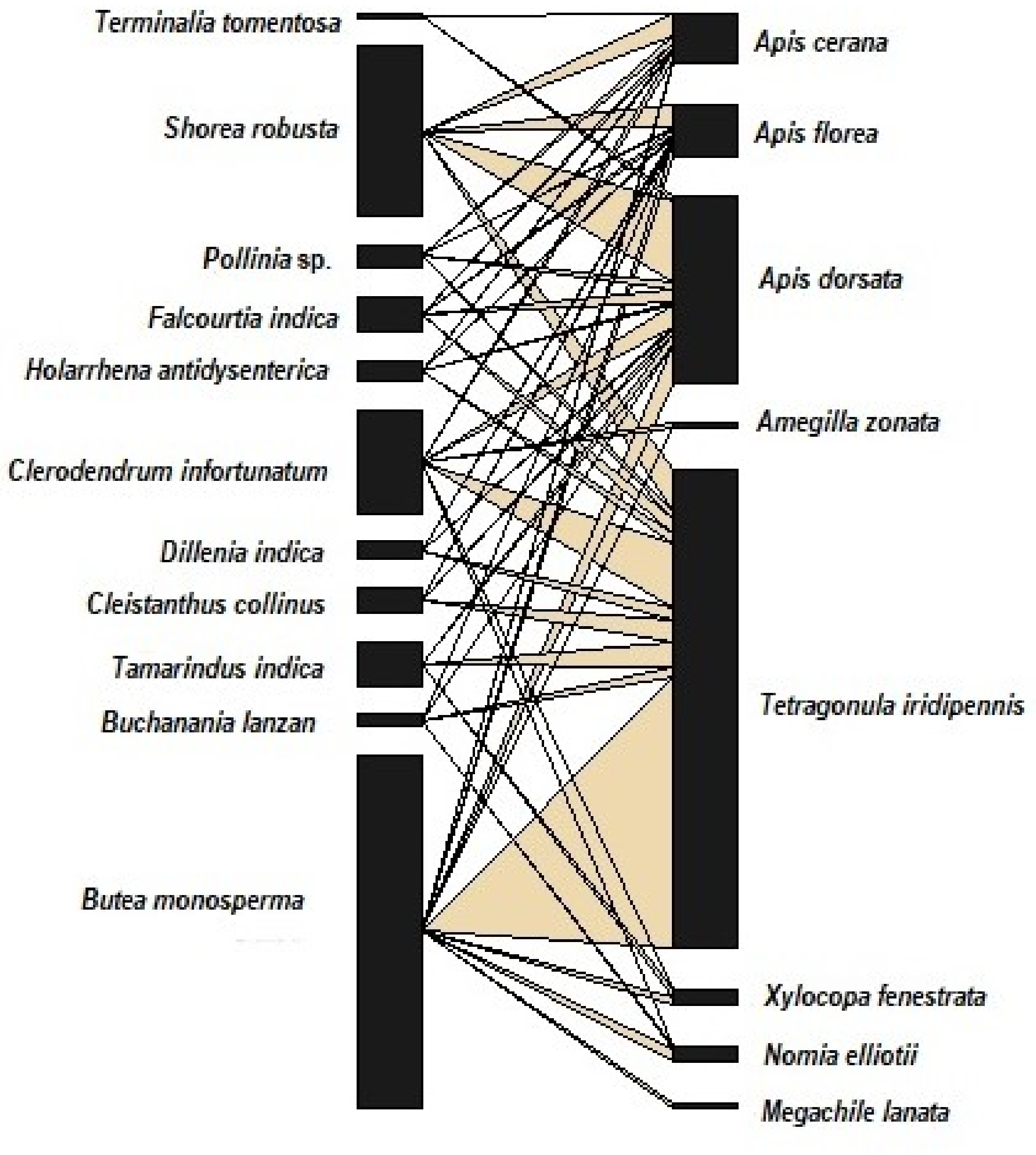


Fig. 6.4. Bipartite web showing the interaction between the bees and plant species in forest areas of KSFD. The boxes on the left are the plant species and boxes on the right represent the bees species. The lines connecting floral functional groups and bees are the interaction events weighted by abundance.

6.4.2. Species level indices in pollination Bipartite network in KSFD

PDI was a measure that assesses the degree of specialization or generality of species interaction, ranging from -1 to 1. The higher value of PDI suggests lofty specialists and the lower value denotes the generalist interaction between plant species and bee species. Most of the studied pollen network plant species exhibited moderate specialization (PDI value 0.9395- 0.738) in their interactions with bee species within the network. PDI value of a few plant species, like- *Cleistanthus collinus*, *Buchanania lanzan*, *Terminalia tomentosa,* and *Butea monosperma*, had signified a relatively high degree of interactions with specialized bee species within the pollen network; the value ranges from 0.965- 0.957.

It was suggested by an effective partner's value of 2.406 that around 2 to 3 significant partners on average within the ecological community were had by *Butea monosperma*. It was signified by the normalized degree (1.00) of *Butea monosperma* that it had a relatively high degree of interaction with potential pollinators. The normalized degree (0.750) of *Clerodendrum infortunatum* suggested that approximately 75% of the potential pollinators in the network were interacted with by the plant species, and its interaction with distinct 2- 3 pollinator partners was clarified by EP values. A normalized degree of 0.500 was possessed by *Falcourtia indica*, *Holarrhena antidysenterica*, *Pollinia* sp., *Buchanania lanzan,* and *Shorea robusta*, indicating that they were interacted with approximately half of the potential pollinators of the network. Also, their EP value, except *Buchanania lanzan,* suggested that distinct 3- 4 pollinator species interacted. *Buchanania lanzan* had an EP value of 2.037, signifying that the plant species was interacted with by around 2-3 pollinator species. An interaction of approximately 37.5% with *Tamarindus indica*, *Cleistanthus collinus* and *Dillenia indica* in the network was shown by potential pollinators. Nevertheless, their EP values differed; 2- 3 potential pollinators were interacted with by *Tamarindus indica*, 1- 2 pollinators with by *Cleistanthus collinus*, and two potential pollinators with by *Dillenia indica*. The normalized value of 0.250 was observed in the case of *Terminalia tomentosa*, indicating 25% interaction. Interaction with approximately 1-2 potential pollinators in the network was shown by EP values.

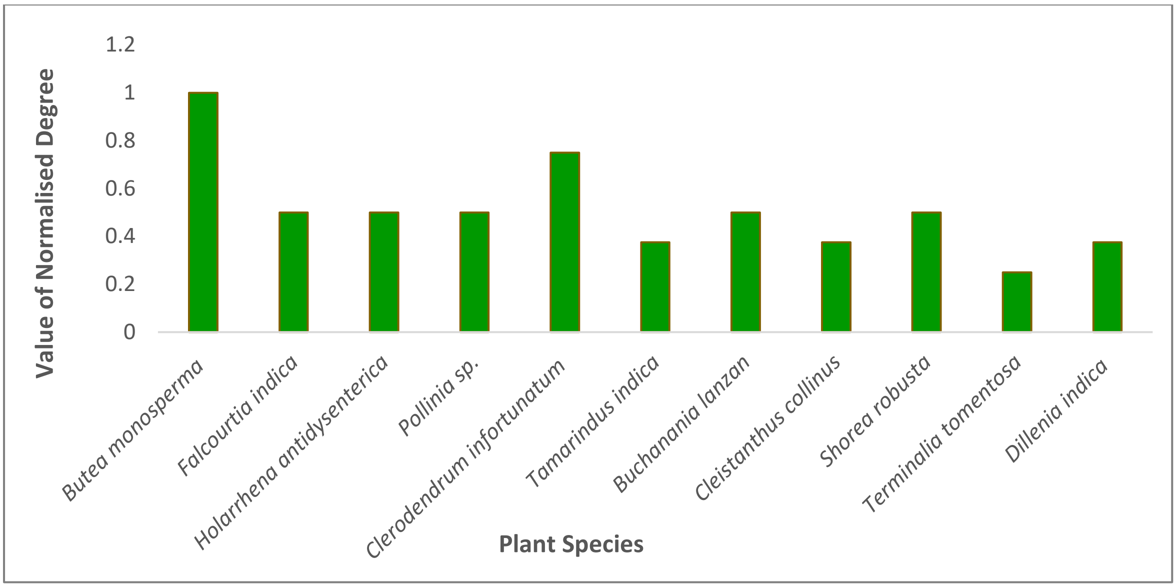


Fig. 6.5. Species level indices of Bipartite network showing the value of Normalized Degree of plant species in forest areas of KSFD. The bar with "green" color represent Normalized Degree.

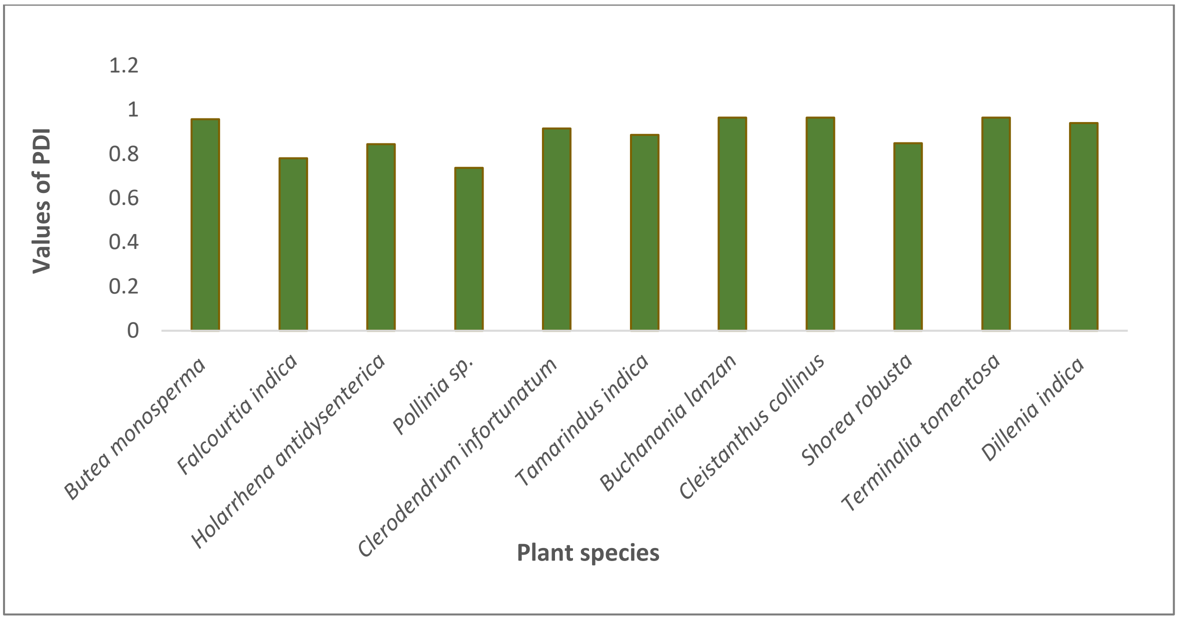


Fig. 6.6. Species level indices of Bipartite network showing the value of PDI of plant species in forest areas of KSFD. The bar with "green" color represent PDI.

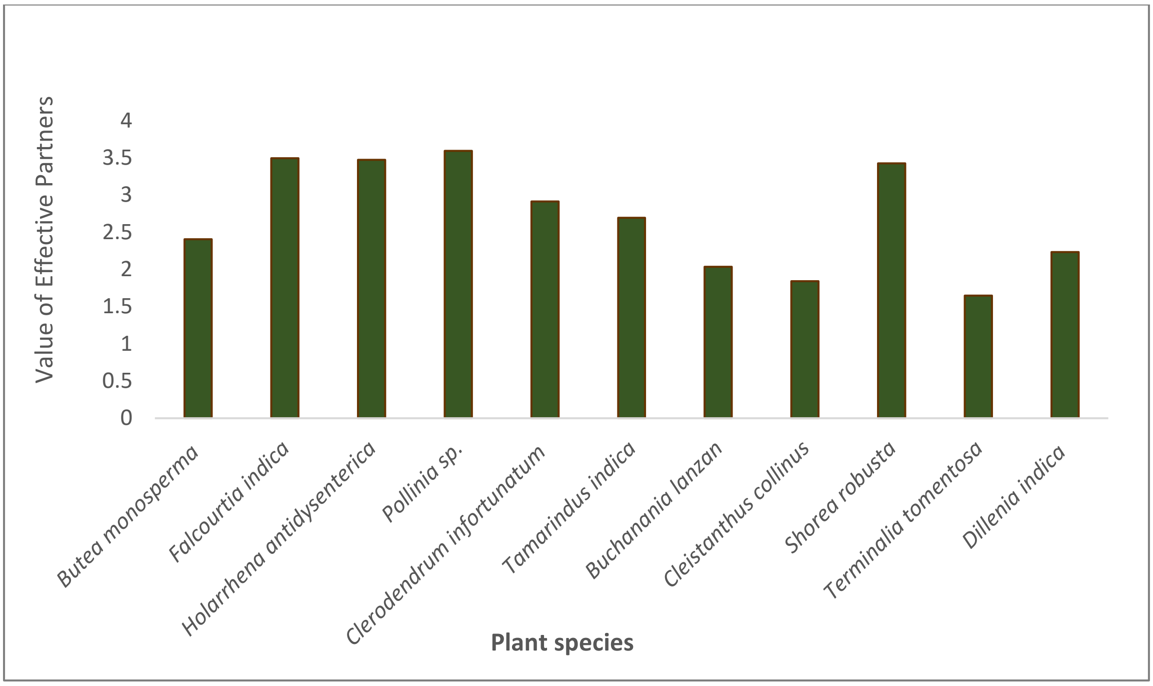


Fig. 6.7. Species level indices of Bipartite network showing the value Effective Partner**s** of plant species in forest areas of KSFD. The bar with "green" color Effective Partner**s**.

6.4.3. Link level indices in pollination Bipartite network in KSFD

The dependence of pollinators (linked species) on plants (hosts) for nectar or pollen resources was represented by HL dependence in a plant-pollinator network. Interactions among different species of pollinators in the same network would be referred to as LL dependence, where the same ecological niches were shared or completed by them. The stability and functioning of the network could be affected by the balance between HL and LL dependence, and ecological implications could arise.

In my study, *Butea monosperma* was preferred by diverse bee species over any other wild plants in the study area. According to the HL dependence, *Butea monosperma* was highly preferable for foraging resources by the two wild bees *Megachile lanata* and *Nomia elliotii* (HL dependence value- 1 and 0.879, respectively). Still, interestingly, their LL was much lower independence. In *Butea monosperma*, the most robust competition or cooperation for resources among other species was faced by *Tetragonula iridipennis* (LL dependence value- 0.77). Social bees were dominantly observed in *Falcourtia indica*, *Holarrhena antidysenterica*, and *Pollinia* sp. Still, their dependency on these plants for nectar or pollens was insignificant, as the HL dependence value ranges from 0.013 to 0.148. However, LL dependence was much higher among these social bees. A higher competition or cooperation (LL dependence value- 0.353 to 0.478) was experienced by *Tetragonula iridipennis* in all three plants. LL dependence of *Apis dorsata* in *Falcourtia indica* and *Pollinia* sp. (value- 0.355, 0.254 respectively) was quite noticeable. In *Pollinia* sp., higher LL dependence (0.314) was faced by *Apis cerana* to the other two plants.

Clerodendrum infortunatum was highly preferred by *Amegilla zonata* for pollen or nectar (HL dependence- 0.917), though LL dependence (0.049) was negligible. Higher LL dependence in *Clerodendrum infortunatum* was observed by *Tetragonula iridipennis* (0.558). *Apis dorsata*, *Apis cerana*, *Apis florea* were highly dependent on *Shorea robusta* for resources with high HL dependence values- 0.446, 0.417, and 0.460, respectively. Still, higher LL dependencies (0.486) were observed only by *Apis dorsata*, implying sharing ecological roles and resources with other species. Significant dependencies towards *Buchanania lanzan*, *Cleistanthus collinus*, *Terminalia tomentosa*, and *Dillenia indica* were not shown by any of the bee species. However, higher LL dependencies were observed in *Buchanania lanzan* (0.8), *Cleistanthus collinus* (0.044), and *Dillenia indica* (0.708) by *Tetragonula iridipennis*. Only *Apis dorsata* and *Apis cerana* were observed in *Terminalia tomentosa* but showed no dependencies. *Apis dorsata* had high LL dependencies (0.8).

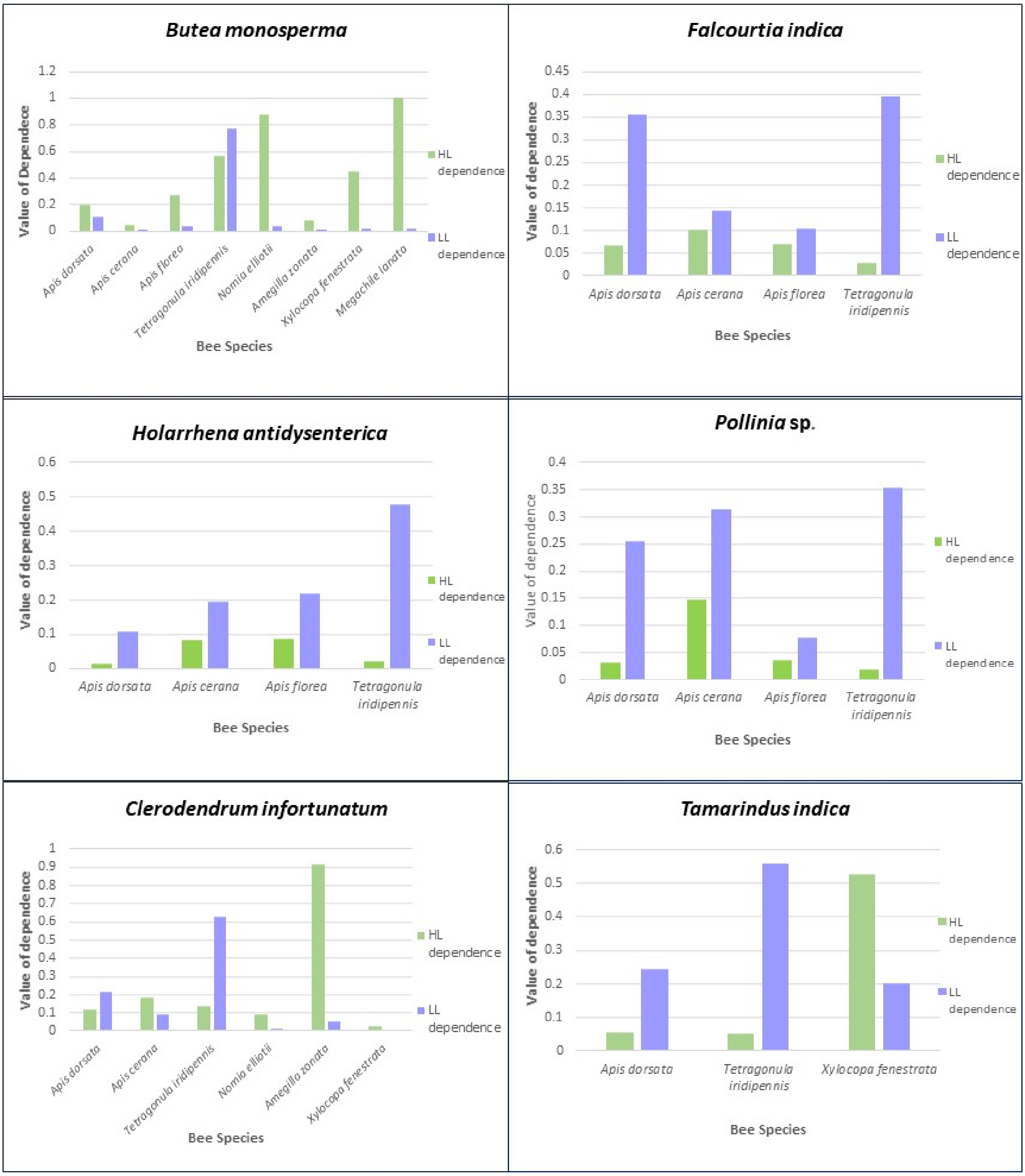


Fig. 6.8. Link level indices of Bipartite network showing the value of HL (Host- Linked) dependence and LL (Linked- Linked) dependence of plant species and bee species interaction in forest areas of KSFD. The bar with "green" color represent HL dependence and the "violet" colored bar represents LL dependence.

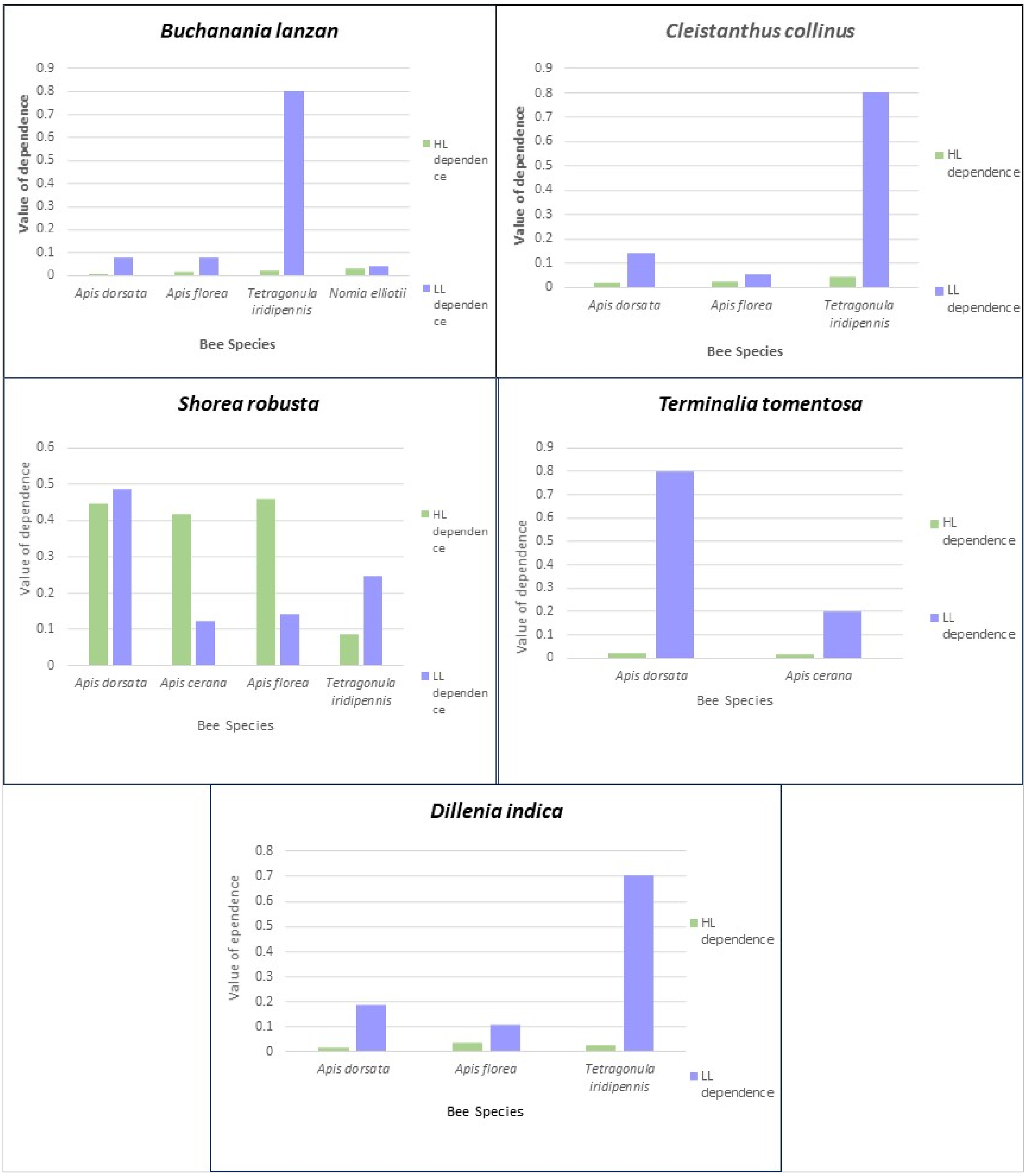


Fig. 6.9. Link level indices of Bipartite network showing the value of HL (Host- Linked) dependence and LL (Linked- Linked) dependence of plant species and bee species interaction in forest areas of KSFD. The bar with "green" color represent HL dependence and the "violet" colored bar represents LL dependence.

6.4.4. Null model of Bipartite network

I computed the NODF (Nestedness Overlap and Decreasing Fill) null model to assess whether the observed network's nestedness was not significantly different from the expected network's nestedness. The statistical significance of NODF ranges from 0 (un-rested) to 100 (fully rested). The observed NODF value in the network was compared by the null model with the distribution of NODF values generated from the 2000 simulations. In this observed network, the NODF null model value was 73.2783, which falls outside the 95% confidence interval. This indicates that the observed network's nestedness was slightly different from the null network's nestedness. This signifies that the network's structure might be influenced by some underlying ecological or biological processes.

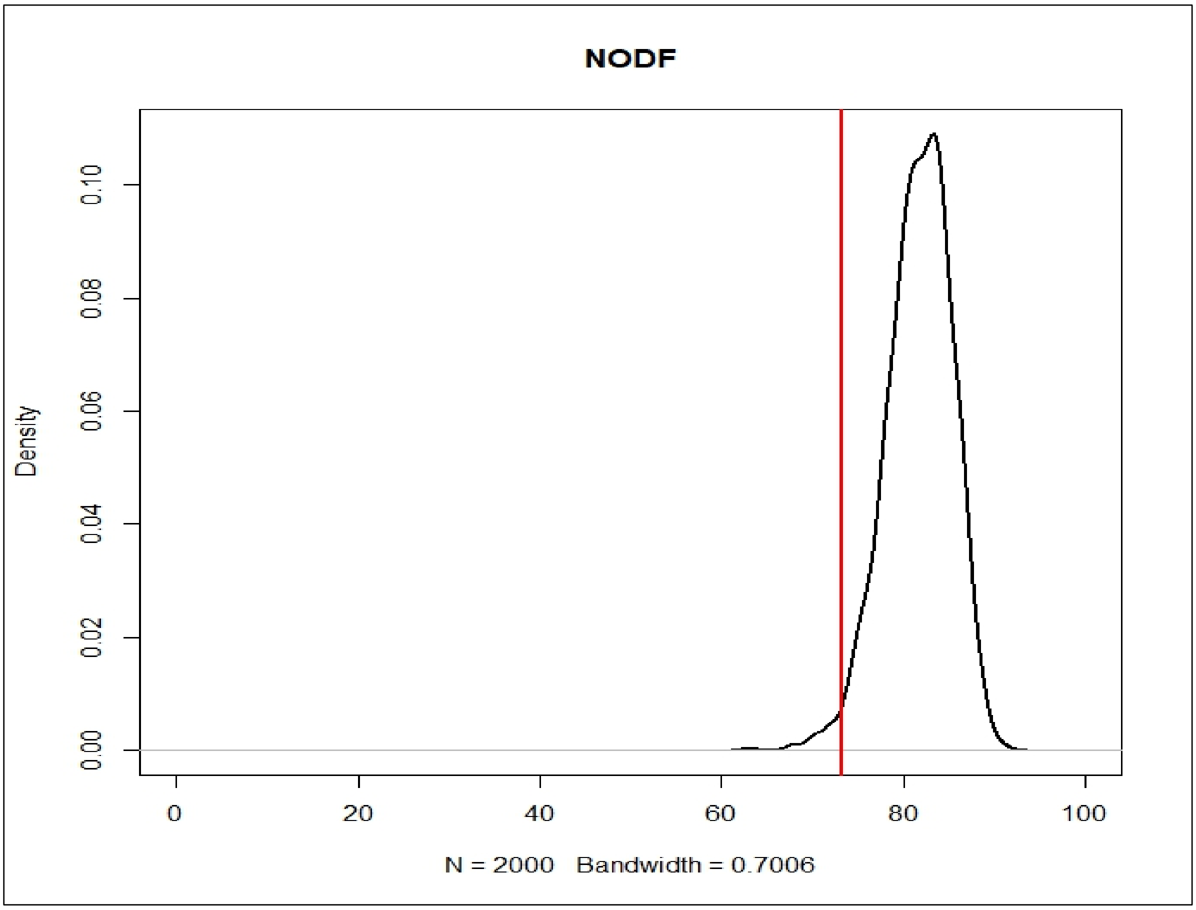


Fig. 6.10. NODF (Nestedness Overlap and Decreasing Fill) null modelled, the values of 100 indicate perfect nestedness.the value of NODF= 73.2783, Bandwidth= 7.006, N=2000.

6.5. Discussion

The plant-pollinator networks in KSFD were composed of flowering plant species and were represented by the three colored pan traps (yellow, white, and blue), along with bees, as pollinators. The floral functional group remained constant and followed similar methodologies across the study area, aiding in the assessment of how network structures responded to natural bee communities across the KSFD. I computed Species-level and link-level indices to understand the interaction and dependencies between flowering plant species and bee species. The most common pattern of structure in mutualistic networks was found to be nestedness (Bascompte et al., 2003), and 60%- 70% of nestedness in the plant-animal mutualistic networks could be illustrated by the relative abundance (Krishna et al., 2008). Additionally, a comparison was made between the real pollination network and the null pollination network to infer the extent of bee interactions with flowering plants.

6.5.1. Pollination network

At first, plant-pollinator interaction was evaluated by connectance; this is the measure of complexity or density of interactions of the pollination network. Passive interaction with three colored pan traps representing the floral functional group was observed during survey (Fig. 5.1 and 5.3); in this observation, most bees interacted with the yellow pan trap with strong weighted interaction. Moderate interaction was observed between bees and the white pan trap, but very few bees were collected from the blue pan trap. Connectance and nestedness were very low in the blue pan trap and high in the yellow pan trap, the white pan trap was moderately observed in terms of connectance and nestedness. *Megachile hera* was only interacted with the white pan trap, and *Nomia elliotii* was collected from the yellow pan trap. *Lassioglossum* sp. was the most dominant species and interacted with all three colored pan traps, expect a similar trend would be observed in wild flowers.

A high abundance of bees was observed in *Butea monosperma*; the flower's coloration is yellowish red, also known as the "Flame of the forest." Bees mostly interacted with "yellowish" colored wildflowers like- *Falcourtia indica*, *Tamarindus indica*, *Buchanania lanzan*, *Cleistanthus collinus*, and *Terminalia tomentosa*. The intensity of the bee's interaction was relatively higher in "yellow" colored oriented wildflowers than in "white" colored wildflowers such as *Shorea robusta*, *Clerodendrum infortunatum*, *Holarrhena antidysenterica*, *Pollinia* sp., and *Dillenia indica*. A strong relationship was exhibited by *Tetragonula iridipennis* with all wild flowering plants except *Terminalia tomentosa*, compared to other bees. *Megachile lanata* and *Amegilla zonata* were only interacted with a particular wild plant, i.e., *Butea monosperma* and *Clerodendrum infortunatum*. In pan trap observation, *Nomia elliotii* was only interacted with the yellow pan trap. Still, *Nomia elliotii* was seen foraging in yellow (*Butea monosperma*) and white (*Clerodendrum infortunatum*) wildflowers. Differences in nestedness might arise from the resource-sharing ability of the different bee species (generalist × specialist) (Pigozzo and Viana, 2010).

6.5.2. Species level indices in the network

Species-level indices (Fig. 5.5- 5.7) in the pollen network were determined by the degree of interaction by the plant species and the significant number of interacting bee partners. In my study, it was observed that most of the flowering wild plants were moderately interacted with by specialized bee species, which were primarily interacted with by a specific subset of bee species. *Cleistanthus collinus*, *Buchanania lanzan*, *Terminalia tomentosa*, and *Butea monosperma* were attracted to and highly associated with more specific bee species.

All potential partners were interacted with by *Butea monosperma* with a high normalized degree in the study area, and the number of effective partners was 2- 3. *Butea monosperma* was recognized as a dominant and widespread plant species in the study area. This plant was not confined only to forest areas but was also observed in the agricultural landscape. A specialized and focused pattern of interactions in the network was shown by *Falcourtia indica*, *Holarrhena antidysenterica*, *Shorea robusta*, and *Pollinia* sp. with a limited number of specific bee partners. *Buchanania lanzan*, despite having a similar average diversity in its interactions, was associated with only a few distinct bee species. A focused pattern of interactions in the network was seen in *Clerodendrum infortunatum*; regardless of high association, only limited number of specific bee partner species were involved. A specialized pattern of interactions within the network, focusing on a particular subset of bee partner species, was observed by the normalized degree values of *Tamarindus indica*, *Cleistanthus collinus*, and *Dillenia indica*. However, only a few effective bee species were associated with *Cleistanthus collinus*. A shallow level of interaction with specialized bee species in the ecological network was exhibited by *Terminalia tomentosa*.

6.5.3. Link level indices in the network

The degree of interaction of host species with pollinators and the degree of dependencies of pollinators on host plants in the pollinator network was explained by link level indices (Fig. 5.8 & 5.9); the competition or cooperation within pollinators for sharing the resources was also clarified. All the wild flowering plants were interacted with by *Apis dorsata*. *Apis dorsata* was highly dependent on *Shorea robusta* and *Butea monosperma*, regardless that a limited interaction with other bee species in *Shorea robusta*, *Falcourtia indica*, *Pollinia* sp., and *Terminalia tomentos*a might have been made by *Apis dorsata*. Specific native flowering plants were highly interacted with by wild bees like *Megachile lanata*, *Amegilla zonata*, *Nomia elliotii*, and *Xylocopa fenestrate* for nectars or pollen with less competition or cooperation level. *Butea monosperma* was strongly relied on by both *Megachile lanata* and *Nomia elliotii*. *Amegilla zonata* was noticed in *Clerodendrum infortunatum* with a robust association. A moderate relationship with *Butea monosperma* and *Tamarindus indica* was revealed by *Xylocopa fenestrata*. Except *Terminalia tomentosa*, all wild flowering flowers were associated with *Tetragonula iridipennis*; moderate or low dependencies for resources had been observed with some flowering plants, but surprisingly, intense interactions (competition or cooperation) with other bee species were experienced by this bee species in all plants except in *Shorea robusta*. *Shorea robusta* was strongly associated with another two *Apis* bees, *Apis florea*, and *Apis cerana*, for nectar or pollen compared to other flowering plant species. Complex interactions with other bee species in any plant pollination network were not encountered by *Apis florea*. In contrast, tension with bee communities within the same ecological network was faced by *Apis cerana* in *Pollinia* sp.

6.5.4. Comparison between real network and null network

The results of comparing the null network with the real network were signified (Fig. 5.10) that the real network was slightly different from the hypothetical network, which means all interactions were occurring moderately in a sub-settled manner. Thus, the role of non-crop plants was essential and beneficial in sustaining the pollen network and bee population. According to Lewinsohn et al. (2006), most abundant species were more generalist, and less abundant species showed a more restricted spectrum range in the ecological network. Plant species with low interaction numbers and frequency were visited mainly by those bee species with higher connectivity and broader distribution in the study area. These features corresponded to nestedness. In this study, *Tetragonula iridipennis* and *Apis dorsata* were the most generalist pollinators or key bee species in the research area, which is consistent with the findings of Martín González et al. (2010).

Chapter - 7
Conclusion

7.1. Introduction

Among the insects, Hymenopterans are considered the most important and highly evolved pollinating insects, and in the order Hymenoptera, bees are the most effective pollinators. In India, the faunal complexity of bees wasn't estimated, but more or less, 1000 species were recorded as realistic. Most of the world's bee species comprise solitary bees (around 85%). Polylectic behavior (collecting pollen from numerous plant species), oligolecthic (collecting pollen from a narrow range of plant species), and monolithic (collecting pollen from only a single species) are exhibited by them. A negligible fraction of bee species in the world is comprised of honey bees, and among them, only four species of honey bees and nearly half a dozen stingless bees were recorded in India. The honeybee population could be managed easily as per pollination requirements. Bees are attracted by the color, structure, and motion of the flowers. Plants are visited by bees for their food, nectar, and pollen. High sugar contents, nectar, and higher nutrition values of pollen are preferred by bees for food, not only getting food but simultaneously, plants are pollinated by bees. Pollination and maintaining genetic diversity are improved by various bee species in plant pollination.

An essential functional role in terrestrial ecosystems is played by pollinators and representing a key E.S.; both wild plant communities and agricultural productivity are vitally maintained by their E.S. Pollination service is primarily served by bees, especially for most wild plants and crops. In India, 160 million hectares of the cropped area, more than 55 million crops were dependent on bees. The quality and quantity of several crops like mustard, sunflower, pigeon pea, apple, mango, citrus, berry, coriander, cucumber, eggplant, tomato, etc., are enhanced by the pollination of both wild bees and honey bees. The crop yield process is played by pollinators as the key players, as plants depend entirely on vectors to transfer their pollen in cross-pollination. The economic and food stability of the country can be achieved by the higher yield of pollinator-dependent crop production. More efficient pollination services can be provided by wild bees than honey bees, especially in crop production. However, due to mismanagement and habitat destruction, the population of native bees has declined worldwide. In India, the basic information about wild bee species diversity, abundance, and community composition still needs to be improved, as well as their contribution to fruit and seed yield and quality in most crops. In Odisha, four bee species out of five species- *Apis cerana*, *Apis dorsata*, *Apis florea*, *Amegilla* sp., and *Xylocopa* sp. experienced a decline of up to 70-90 percent, was suggested by the farmers in a case study (2017). On a global platform, the importance of pollinators was acknowledged by the Convention on Biological Diversity with the establishment of the International Initiative. A project involving seven nations, including India, was incorporated to identify practices and build capacity to manage pollination services. In past years, few attempts have been initiated to assess bee diversity, documentation, and conservation actions. Before any conservation aspects, the bee assemblage of a particular local habitat needs to be evaluated. The magnitude of a decline in pollinators and pollination services can't be assessed if they can't be correctly identified by experts; a risk of not knowing what it is we are trying to conserve is being invited.

Among all Indian states, West Bengal is recognized as an agrarian State, with a cropping intensity of 184%, and is known for cultivating numerous pollinator-dependent crops (West Bengal State Portal, 2022). But, the information and literature regarding bee pollinators could be more extensive and scattered. Purulia is located in the western part of West Bengal, acting like a funnel. The tropical monsoon current from the Bay of Bengal is funneled to the subtropical parts of northwest India. Savana climate has been observed, and 50% of the rainfall is carried away as runoff due to undulated topography. The district is mainly covered by residual soil formed through bedrock weathering. The middle and southern portions of Purulia were considered to have the highest risk of drought due to the undulating red and lateritic zone (Goswami, 2019). Water stress in the ecological productivity of the area was caused by decreasing rainfall and increasing aridity (low P/PET). The doctoral study was conducted in KSFD, located in the southern part of the Purulia district. For the first time, the diversity patterns in contrast to the present anthropogenic activities and the role of non-crop plants in sustaining the present plant-pollen network across selected habitats in KSFD were documented and investigated in the current study.

7.2. Anthropogenic activities affect the bee community

Twenty-five species were recorded in the present study, succeeding average 96.3% completeness in documentation. A reference point was generated from this study for future investigations, monitoring, and creating conservation strategies. Bee species belong to three families: Apidae (61%), Halictidae (31%), and Megachilidae (8%). The abundance of bee species was influenced less significantly by the meteorological parameters. Low bee diversity and evenness were observed in mixed forests, which could result from the imbalance in bee species distribution due to different floral patterns and flowering periods of various plant species communities. Moderate diversity and evenness were documented in the Sal forest, attempting to maintain a balance in species composition because of the dominance of one plant species (*Shorea robusta*). Despite that, a moderate level of dissimilarities in bee community composition was exhibited between mixed forest and Sal forest, indicating the sharing of similar environmental characteristics and ecosystem functions.

The composition of bee communities in agricultural landscapes was shown to have significant dissimilarities from the natural ecosystem. The presence of different mixes of crops in the agricultural landscape led to not only the most diverse bee species composition but also high distribution in evenness. Among crops, a high level of evenness in the distribution and the most diverse bee species composition was observed in crops (tomato and eggplant) of the family Solanaceae. Especially "buzz" pollinators are required to pollinate crops of this family. A high degree of dissimilarity in bee species composition was maintained by these two crops with all the other crops. A high level of similarity was observed between two oilseed crops, i.e., mustard and sunflower.

The fast-growing urbanization is one of the significant threats to biodiversity and ecosystem services. The regulation ecosystem service of bee pollination, plays a role in wild plant reproduction and crop production and contributes to human well-being and the environment. Ecosystem services provided by bees are increased in response to their diversity. Even the diversity reaction can strengthen the pollination ecosystem services against environmental changes. Hence, ecosystem services are stabilized by bee diversity through the utilization of response diversity (Cariveau et al., 2013). In agriculture, enhanced and stabilized crop yields and food quality are attributed to diverse bee species (Brittain et al., 2013; Garibaldi et al., 2013).

As the study was done in an agroforestry ecosystem, not in any urbanized area (HFI is below 15 in most areas), we noticed an overall moderate diversity index in the bee community. Negligible HFI zones were significantly fewer, indicating less dense forest patches were present and leading towards converting the natural habitat landscape to the agricultural landscape. The presence of anthropogenic impacts in the forest area was demonstrated by the results of the HFI map. Habitat alteration was visible due to excessive agricultural practices, also documented during the socioeconomic survey. In the agroforestry ecosystem, wild trees can be found on the border of the agricultural land, which sustains the wild bee population and diversity. The strength and stability of ecosystem services, i.e., crop yield and quality, were consistently increased by high bee diversity. Moderate bee diversity in the community was still found despite the alteration of the landscape and increasing anthropogenic pressure.

Most of the residents of the study area were found to belong to below the poverty level and an Indigenous community; dependence on forest timber for firewood was high among them because they could not purchase LPG. NTFP was primarily relied upon for household purposes and as an earning source. Agriculture practices were prominently preferred and flourished throughout the study area. Mixed cropping practice was developed in significant parts of the Kangsabati River basin. The aridity index of the southern area of the district is >7.0 (Kar et al., 2020). Considerable environmental degradation was experienced in the region due to the encroachment of deforestation and bandh sites for the flourishment of agricultural practices (Aggarwal et al., 2009). However, the eco-friendly agriculture practice needed to be maintained, and the use of excessive pesticides was noticed. Subsistent and unskilled agriculture was practiced by less literate farmers. The unskilled farmers, low organic matter, greater use of pesticides, and high irrigation had been used to complete the needs of the more significant dependent population, decreasing land productivity. The immature soil with low productivity and a double cropping pattern was directed toward land degradation. Even predominant land degradation was observed because of the low forest cover (<6%) in larger parts of the district (Mahala, 2016). Also, considerable wasteland was observed in the district (Kar et al., 2020). A similar observation was observed through the extracted HFI map of the studied area, indicating a solid degree of undergoing anthropogenic involvement in rapidly altering and destructing natural habitat.

In the agricultural context, non-crop plants are beneficial for bees, as the crop's flowering period is shorter than the bees' life cycle; hence, insufficient rewards (such as pollen and nectar) are provided by non-crops plants (Calabuig, 2000). Pollinator movement was observed across the agricultural landscape, between natural and semi-natural patches (Kremen et al., 2007; Tscharntke et al. 2005), seeking refuge and forage resources absent elsewhere (Coll, 2009). In this doctoral study, 25 species were documented, among which 21 are wild and rare bee species that need natural habitats for their nesting and breeding sites. It was concluded that bee communities will be affected by anthropogenic activity in the near future, as the absence of natural habitats can accelerate the decline of bee species.

7.3. The role of non-crops in sustaining the pollen networks

A mutualistic association known as pollinator interaction plays a key functional role in the ecosystem, as the reproduction of plant species is facilitated by pollinators, and feeding opportunities for the bees are provided by plants (Ollerton et al., 2011). The plant-pollinator relationship is threatened by habitat alteration, changes in agriculture practices, decreasing diversity of flowers, and increasing use of pesticides (Ollerton et al., 2014; Goulson et al., 2015).

The mutualistic relation between wild plants and bee species was also aimed to be investigated in this study; polylectic or generalist bee species like *Tetragonula iridipennis*, *Lassioglossum* sp., and *Apis dorsata* widely interacted with all wild flowering plants. Particular species were specific to some oligolectic or specialist wild bee species. Complex solid interaction with other species for resource sharing in the network of every plant species was experienced by *Tetragonula iridipennis*, a specialist bee species. Negligible completion for resource sharing was observed by all oligolectic species in the ecological network. The structural and functional characteristics of the pollen network were maintained by generalist bees, which were the key species. Even too specific effective partners were selected by some plants. In the study area, an association with most bees was developed by *Butea monosperma*, the most widespread and generalist flowering plant species. A moderate occurrence of the pollen network in a sub-settled manner was observed in the study area. The network's structure may be shaped by some underlying ecological or biological processes.

Specialist bee species like *Megachile lanata*, *Nomia elliotii*, *Amegilla zonata*, *Xylocopa fenestrata* and *Megachile hera* were dependent on specific plant species for pollen or nectar. The survival of this species and the disruption of the plant-pollinator network can be affected by the loss of these specific plants. A preference for a few bee species as effective partners was observed even in specialist plants; the reproductive gain of the plant species could be affected by the loss of those species. Even the long-term health and diversity of the plant-pollinator community, as well as the short-term resilience of the network of plants and pollinators to disturbances, are affected by the loss of a keystone floral resource (Sandacz et al., 2023), and also accelerate the decline of crop production eventually. Rare bees can be conserved by conserving plant-rare bees interaction and locating nesting sites of rare bees in heterogeneous landscapes (Sydenham et al., 2022).

In natural habitats, excellent nesting sites for many bee species are observed in wild plants. The tree's trunk was preferred as a nesting site by *Tetragonula iridipennis*, the most generalist bee species in this study. A significant role in sustaining pollen networks, which will benefit crop pollination, is played by wild plants or non-crop plants; with this, my second research question is concluded. Our needs for food production in the near future can be fulfilled by sustaining the pollen network, necessitating the protection of our wild plant species and natural habitat. Efficient roles in the pollination network were being contributed by bees.

7.4. Concluding remarks and key recommendations

Inventorial knowledge of bee pollinators in different habitats in KSFD is propagated by my doctoral thesis. In this work, 25 bee species of three families were identified, among which 21 were wild and rare bees, which was documented for the first time. A diverse bee species constitutes the agroecosystem, and their abundance was evenly distributed among crops, indicating a strong crop pollination in the study area. The involvement of wild plants was efficient in maintaining the pollen network and indirectly contributed to crop pollination. Specific trees like *Clerodendrum infortunatum* were foraged by particular wild bees like *Nomia elliotii*; hence, to sustain and increase the bee population, the forest department requires the cultivation of those tree saplings and restoring heterogeneous landscapes. A precise scenario was obtained by involving wild plants in crop pollination. Hence, the protection of natural habitats is considered essential for better crop yields. Also, well-known elephant corridors are comprised of these forest patches. So, to maintain overall biodiversity and ecosystem function, necessary action shall be taken by the government sector to reduce the rate of habitat alteration, deforestation, and forest fire.

Necessary action must be taken by the government and local NGOs to initiate small-scale businesses from NTFPs or handicrafts involving women and older people, supporting economically, especially for the residents under the poverty level. Introduction of alternative jobs opportunity is needed to be introduced among youth, to reduce the rate of excessive unskilled agriculture practices which leaded to environmental degradation and habitat alteration. A campaign is required to introduce alternative biofuels for firewood to reduce its usage.

The region's inclination towards agricultural practices was highlighted by socio-economic surveys; the continuous increases in deforestation and wasteland fulfil the purpose. To overcome further drastic changes in the ecosystem, scientific agriculture practices need to be included by the state agriculture department, like- the need to promote Integrated Pest Management (IPM) and also need to design similar programs to enable farmers to gain from ecosystem services, support, and endorse organic farming and encourage farmers to reduce the usage of inorganic pesticides, to acknowledge and accept pollination as an essential element in agricultural extensions services and initiate action in favour of pollinator-friendly agriculture practices. Awareness generation programs among farmers and residents, the campaign against harmful chemicals affecting pollinators, and the establishment of a pollinator conservation resource centre for native bees are required to be incorporated by the National Bee Board, and state agriculture departments, where regional plant list, habitat conservation guides, and other relevant resources can be quickly located.

In this region, small-scale farmers were higher than large-scale farmers, and both needed to be familiar with pollination phenomena and trained in skilled agriculture practices. Even with the introduction of Indigenous knowledge-based practices with a scientific approach and bee culture of honey and wild bees, an abundance of diverse pollinators can be restored quickly. A source of the solution to current challenges may be found in them. The implications of this research work benefit scholars, scientists, and R&D agents; further investigation and monitoring of pollinators in KSFD or Purulia district, West Bengal, can be conducted by them. This study is recognized as the baseline study in KSFD. The role of plant diversity and wilderness in and around agricultural land should be thoroughly investigated by future research. The effects of agriculture intensification (use of chemicals and mechanization, etc.) on bee diversity in agroecosystems, the study of bee diseases, and the role played by predators in the decline of the bee population are to be explored, locating nesting sites and foraging distance of each wild bee species need to be explored to ensure that an adequate amount of proximity is maintained between agriculture land and natural ecosystem.

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Plate- 8
Species of Family Apidae

Amegilla calcifera

Amegilla violacea

Amegilla zonata

Apis cerena

Apis dorsata

Apis florea

Ceratina compacta

Ceratina hieroglyphica

*Ceratina smaragdu*la

Plate- 9

Species of Family Apidae

Ceratina species

Tetragonula iridipennis

Thyreus species

Xylocopa aestuans

Xylocopa fenestrata

Xylocopa magnifica

Species of Family Megachilidae

Megachile lanata

Megachile hera

Plate- 10
Species of Family Halictidae

Lassioglossum species

Lipotriches species

Nomia crassipes

Nomia elliotii

Nomia iridescens

Nomia strigata

Nomia westwoodi

Pseudapis oxybeloides

Plate- 11
Wild plants

Clerodendrum infortunatum

Buchanania lanzan

Butea monosperma

Falcourtia indica

Shorea robusta

Appendices

Appendix I – Bray-Curtis values among different habitats.

	Agriculture Landscape	Mixed forest
Mixed forest	0.7906913	_
Sal forest	0.8934188	0.6607460

Appendix II– Bray-Curtis values among different crops.

	Mustard	Pigeon Pea	Cucumber	Sunflower	Sesame	Green gram	Ridge gourd	Eggplant
Pigeon Pea	0.4688157	_	_	_	_	_	_	_
Cucumber	0.4285714	0.7797271	_	_	_	_	_	_
Sunflower	0.3044719	0.4498715	0.5437978	_	_	_	_	_
Sesame	0.6272799	0.7155797	0.3837209	0.5817875	_	_	_	_
Green gram	0.4939543	0.4884393	0.7139738	0.3253362	0.6628272	_	_	_
Ridge gourd	0.4539341	0.5804511	0.4235727	0.4413965	0.4209622	0.5093633	_	_
Eggplant	0.6588921	0.5078189	0.9011329	0.6613757	0.7082936	0.6932212	0.6298039	_
Tomato	0.9796126	0.9126214	0.8620690	0.8972648	0.7598784	0.9141104	0.8054299	0.6775033

Appendix III- Species Level Attributes of plant species.

Plant Species	**Normalised Degree**	**PDI**	**Effective Partners**
Butea monosperma	1.000	0.9578255	2.4062
Falcourtia indica	0.500	0.7809524	3.4949
Holarrhena antidysenterica	0.500	0.8441558	3.4727
Pollinia sp.	0.500	0.7380952	3.5942
Clerodendrum infortunatum	0.750	0.9153061	2.9148
Tamarindus indica	0.375	0.8867925	2.6936
Buchanania lanzan	0.500	0.9642857	2.0368
Cleistanthus collinus	0.375	0.9650794	1.8414
Shorea robusta	0.500	0.8491172	3.4266
Terminalia tomentosa	0.250	0.9642857	1.6494
Dillenia indica	0.375	0.9395604	2.2332

Appendix IV- Link Level Attributes between plant species and bee species.

HL dependence								
Plant species	*Apis dorsata*	*Apis cerena*	*Apis florea*	*Tetragonula iridipennis*	*Nomia elliotii*	*Amegilla zonata*	*Xylocopa fenestrata*	*Megachile lanata*
Butea monosperma	0.2005013	0.046296	0.265487	0.568380	0.878788	0.083333	0.444444	1
Falcourtia indica	0.0676692	0.101852	0.070796	0.029098	0.000000	0.000000	0.000000	0.000000
Holarrhena antidysenterica	0.0125313	0.083333	0.088496	0.021339	0.000000	0.000000	0.000000	0.000000
Pollinia sp.	0.0325815	0.148148	0.035398	0.017459	0.000000	0.000000	0.000000	0.000000
Clerodendrum infortunatum	0.1203008	0.185185	0.000000	0.135790	0.090909	0.916667	0.027778	0.000000
Tamarindus indica	0.0576441	0.000000	0.000000	0.051406	0.000000	0.000000	0.527778	0.000000
Buchanania lanzan	0.0050125	0.000000	0.017699	0.019399	0.030303	0.000000	0.000000	0.000000
Cleistanthus collinus	0.0200501	0.000000	0.026549	0.043647	0.000000	0.000000	0.000000	0.000000
Shorea robusta	0.4461153	0.416667	0.460177	0.088264	0.000000	0.000000	0.000000	0.000000
Terminalia tomentosa	0.0200501	0.018519	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Dillenia indica	0.0175439	0.000000	0.035398	0.025218	0.000000	0.000000	0.000000	0.000000

Appendix V- Link Level Attributes between plant species and bee species.

LL dependence								
Plant species	*Apis dorsata*	*Apis cerena*	*Apis florea*	*Tetragonula iridipennis*	*Nomia elliotii*	*Amegilla zonata*	*Xylocopa fenestrata*	*Megachile lanata*
Butea monosperma	0.10540	0.0065876	0.039526	0.77207	0.038208	0.0013175	0.0210804	0.01581
Falcourtia indica	0.35526	0.1447368	0.105263	0.39474	0.000000	0.000000	0.000000	0.000000
Holarrhena antidysenterica	0.10870	0.1956522	0.217391	0.47826	0.000000	0.000000	0.000000	0.000000
Pollinia sp.	0.25490	0.3137255	0.078431	0.35294	0.000000	0.000000	0.000000	0.000000
Clerodendrum infortunatum	0.21525	0.0896861	0.000000	0.62780	0.013453	0.0493274	0.0044843	0.000000
Tamarindus indica	0.24211	0.000000	0.000000	0.55789	0.000000	0.000000	0.2000000	0.000000
Buchanania lanzan	0.08000	0.000000	0.080000	0.80000	0.040000	0.000000	0.000000	0.000000
Cleistanthus collinus	0.14286	0.000000	0.053571	0.80357	0.000000	0.000000	0.000000	0.000000
Shorea robusta	0.48634	0.1229508	0.142077	0.24863	0.000000	0.000000	0.000000	0.000000
Terminalia tomentosa	0.80000	0.2000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Dillenia indica	0.18919	0.000000	0.108108	0.70270	0.000000	0.000000	0.000000	0.000000

List of Publications, Conferences and Workshop

Paper Published:

1. Pallabi Das & V.P. Uniyal. 2023. Diversity of bees in two crops in an agroforestry ecosystem in Kangsabat South Forest Division, Purulia, West Bengal, India. Journal of Threatened Taxa. 5(3): 22889–22893.

DOI :https://doi.org/10.11609/jott.8273.15.3.22889-22893

ISSN No: 0974-7907 (Online), 0974-7893 (Print)

Abstract Published in Conference:

1. Poster Presentation "Acitivity of *Amegilla* bees in various crops in Kangsabati South Forest Division". ATBC, India, 2023.

2. Oral Presentation "Diversity of bees as visitors of various crops in South Kangsabati Forest Division", ICCC, Malaysia, 2022.

3. Oral Presentation "Ecological notes on Subfamily Xylocopinae bees as visitors of various crops in South Kangsabati Forest Division", 2nd ICBPC, Pakistan, 2022.

Workshop attend:

1. Remote sensing & GIS Technology and application for University teachers & Government officials" from Indian Institute of Remote Sensing, Dehradun, 2020.

CERTIFICATE

AWARDED TO

Ms. Pallabi Das

FOR

Oral presentation

IN THE
2ND INTERNATIONAL CONFERENCE ON BEE POLLINATION & CONSERVATION,
ON MAY 20, 2022, AT MNS UNIVERSITY OF AGRICULTURE MULTAN, PAKISTAN

Prof. Dr. Shafqat Saeed
Director IPP, MNS-UAM

INTERNATIONAL CONGRESS ON

IMPACTS OF CLIMATE CHANGE ON AGRICULTURE, ECOSYSTEMS AND HUMAN HEALTH (ICCC 2022)

16 – 18 NOVEMBER 2022, MIRI, MALAYSIA

CERTIFICATE OF APPRECIATION

Presented to

Ms Pallabi Das

in recognition of your contribution as on-line presenter in ICCC 2022

16 – 18 NOVEMBER 2022

Prof Dr V Sivaram, ICCC 2022 Chair

59th ANNUAL MEETING OF THE ASSOCIATION FOR TROPICAL BIOLOGY AND CONSERVATION

Certificate
of presentation

Awarded to

Pallabi Das, V P Uniyal, Kailash Chandra

in sincere appreciation for the valuable contribution
"Activity of Amegilla bees in various crops in Kangsabati South Forest Division, West Bengal, India"
presented as part of the **poster session**
"Food system and plant ecology".

Coimbatore, India, July 02-06, 2023

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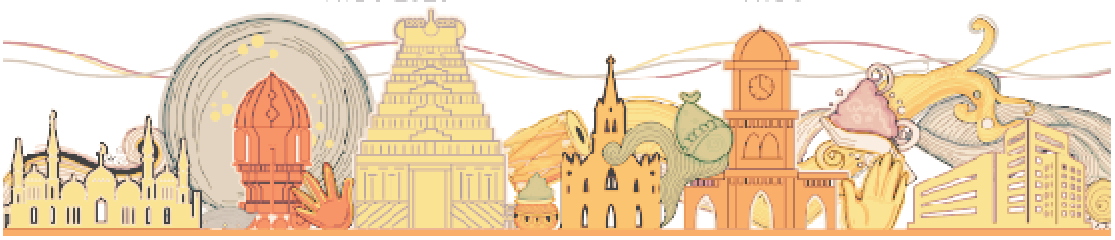

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Journal of Threatened Taxa | www.threatenedtaxa.org | 26 March 2023 | 15(3): 22889–22893

ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

https://doi.org/10.11609/jott.8273.15.3.22889-22893

#8273 | Received 21 November 2022 | Final received 20 January 2023 | Finally accepted 01 March 2023

SHORT COMMUNICATION

Diversity of bees in two crops in an agroforestry ecosystem in Kangsabati South Forest Division, Purulia, West Bengal, India

Pallabi Das [1] & **V.P. Uniyal** [2]

[1,2] Wildlife Institute of India, Chandrabani,, Dehradun, Uttarakhand 248001, India.
[1] pallabidas4@gmail.com (corresponding author), [2] uniyalvp@gmail.com

Abstract: The investigation study assesses the diversity of bees in Brinjal *Solanum melongena* L. and Ridge Gourd *Luffa acutangula* L. crop field from agroforestry ecosystem in South Kangsabati Forest Division, India. The study was carried out in May 2021 to May 2022 that based on transect, focal observation and pan trap samplings. A total of 1,085 individuals were identified during the field work, belonging to three family seven genera (*Apis*, *Tetragonula*, *Xylocopa*, *Ceratina*, *Amegelia*, *Nomia*, and *Megachile*) and seventeen species, the non *Apis* bees (63.78%) were most abundant than *Apis* bees (36.22%). In brinjal, Shannon diversity index of bees is 2.12 and Shannon evenness index is 0.35, whereas, Shannon diversity index in ridge gourd was 1.94 and Shannon evenness index is 0.3. The observations signify greater diversity and population of wild bees. The natural habitat close to agricultural land helps to sustain the diversity and population of wild bees, which enhance the crop quality and yield.

Keywords: Agro forestry, *Apis* bees, eggplant, non *Apis* bees, pollinator, Ridge Gourd, *Tetragonula*, *Xylocopa.*

Now-a-days, agroforestry is an important ecosystem especially in a tropical country and it is an intensive land management system. It consists of agriculture systems and have potential biodiversity conservation sites. The agroforestry ecosystem provide rural livelihood alongside biodiversity conservation in a sustainable land use system. This system is a transitional process from conventional agricultural practices to agro-ecological agricultural practices (Souza et al. 2014). Combination of crops and diverse plants species in forest provide a rich insect diversity due to increased niche diversity than any agro-ecosystems (Stamps & Linit 1998). Heterogeneous agroforestry ecosystem provides floral resources for pollinators (Sinu & Shivanna 2007). Habitat loss and intensification of agricultural practices threaten wild as well as domestic pollinators. Agroforestry ecosystem provides them suitable nesting sites and floral resources, enhancing their pollination services to crops at a landscape level (Sutter 2017; Kay et al. 2019). Bees are the primary pollinators and roughly cover 90% of world plant population (Winfree 2010).

In agriculture land bees are the essential pollinators for pollination as well as crop production. Non *Apis* species are effective pollinators than honey bees (Javorek 2002; Kreman et al. 2002), but they both can together enhance crop production (Greenleaf & Kreman 2006). Brinjal *Solanum melongena* L. and Ridge Gourd *Luffa acutangula* L. are important and widely cultivated crops across the studied area and also bee-attracting vegetable crops. Buzz pollinators are effective pollinators for solanaceous (Brinjal) and cucurbitaceous (ridge gourd) crops. Brinjal flowers have abundance of pollen but to expel the pollen requires vibration by insects called 'buzz pollination'. Wild bees are efficient in buzz pollination than honey bees (Buchmann 1983; Herren & Ochieng 2008). Natural forest is a suitable habitat for wild bees but due to extensive deforestation they are

Editor: Anonymity requested. **Date of publication:** 26 March 2023 (online & print)

Citation: Das, P. & V.P. Uniyal (2023). Diversity of bees in two crops in an agroforestry ecosystem in Kangsabati South Forest Division, Purulia, West Bengal, India. *Journal of Threatened Taxa* 15(3): 22889–22893. https://doi.org/10.11609/jott.8273.15.3.22889-22893

Funding: Self-funded.

Competing interests: The authors declare no competing interests.

Acknowledgements: The authors are thankful to the West Bengal Forest Department, Hymenoptera Section of Zoological Survey of India (ZSIK), Director and Dean of Wildlife Institute of India.

in threat. This investigation was carried out to generate information about the diversity of bees in pollination dependent crops in an agroforestry ecosystem.

Study Area

The study was conducted in an agroforestry ecosystem in western part of West Bengal, India. The studied area is in Kangsabati South Forest Division in Purulia. The forest division is situated between 23.166–22.833 N & 86.666–87.000 E, covering 310.27 km^2 areas, which are continuations of the Chotanagpur Plateau (Figure 1). Mixed cropping system is practiced dominantly in the studied area. Fourteen plots were selected randomly throughout the South Kangsabati Forest Division on the basis of easy accessibility and densely blooming flowering plots. These fourteen plots were equally divided into seven plots for each crop. The experimental study was conducted in various farm lands from May 2021 to May 2022 in the eggplant and ridge gourd crops fields.

Methods

All bee surveys were conducting from 0830 h to 1630 h, split in three time hours: 0830–0930 h, 1130–1230 h, & 1530–1630 h. Bees are active in warm, sunny days so rainy and cloudy days were avoided for the unbiased data. Three methods—transect, focal observation (15 mins), and pan traps (yellow, white, blue colored pan traps)—were followed throughout one year of survey. The transect length was 100 m with 2-m breadth on each side (Sutherland 1996). In focal observation (Gibson et al. 2011), a 1 m^2 flowering plot was selected randomly and bees were observed for 15 mins. Pan traps of three different color sets were used for passive sampling (Westphal et al. 2008). Yellow, white, blue pan traps were used which were painted with UV-bright colors. Five clusters of pan traps were installed where each cluster was separated from another by a distance of 15 m. Each cluster contained three sets of pan traps filled with 400 ml soapy water. The species not identified in the field were collected through sweep net, killed by ethyl acetate, and preserved in 70% ethanol for future

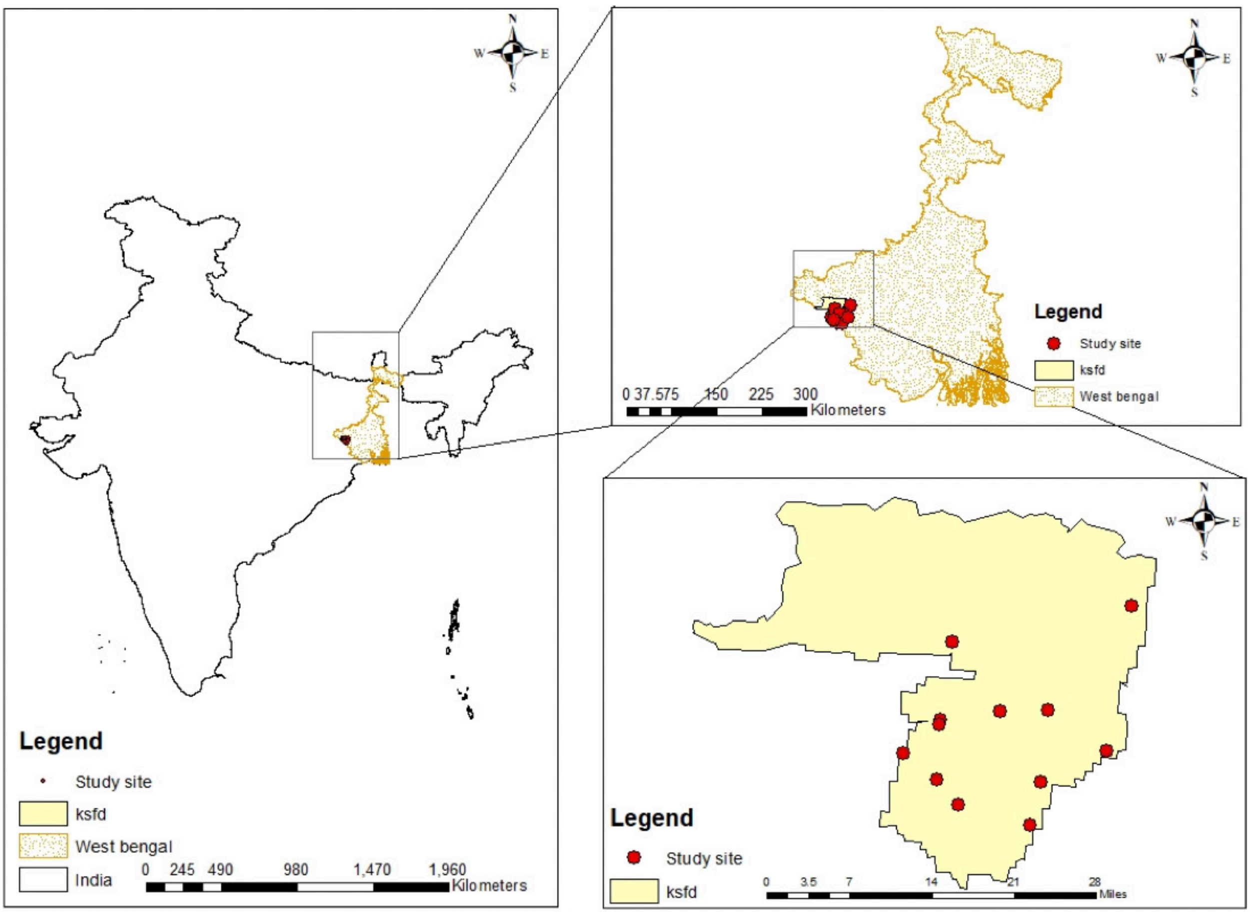

Figure 1. The study site Kangsabati South Forest Division (KSFD), Purulia, West Bengal, India.

reference. We followed Bingham (1897) and Michener (1974, 1994, 2007) for bee identification.

We observed diversity and abundance of bees by observing bees visiting Brinjal and Ridge Gourd flowers. These data were used for analyzing bee diversity by Shannon diversity index (H') and Shannon evenness index (J'). The number of bees data (sampled via transect, focal observation & pan trap) were pooled in each crop independently for analysis of richness and abundance. The data were analyzed using Past Software 3.4.

Shannon Diversity Index ($H' = -\Sigma p_i * ln(p_i)$)

Shannon evenness index (J) = H/lnS

Relative Abundance= (N_i/N)*100

Where, S is the total number of species and p_i is the proportion of the entire community made up of species i. N_i is the abundance of species i and N is the total of all species encountered.

Results and Discussion

A total of 1,085 bee individuals were encountered belonging to three families (Apidae, Halictidae, Megachilidae), seven genera and 17 species during the survey. *Tetragonula iridipennis* was most dominant species with 262 individuals followed by *Apis florea* (182 individuals) and *Nomia elliotii* (169 individuals). Most of the bee species belonging to the family Apidae were observed during the study. During the survey time, non *Apis* bees (63.78%) were dominant in abundance than *Apis* bees (36.22%).

Among these two vegetable crops, Brinjal had most diverse and abundant number of bee visitors. Shannon diversity index of bees in eggplant crop is 2.12 and Shannon evenness index is 0.35; the most abundant bee species was *Tetragonula iridipennis* (33.97%) followed by *Megachile lanata* (14.83%), *Nomia elliotii* (14.59%), *Xylocopa fenestrate* (9.09%). Some rare bees like *Megachile hera* (0.7%), *Nomia westwoodii* (1.7%), and *Ceratina hieroglyphica* (1.2%) were also encountered. The pollinator fauna of Brinjal consist of two species from Megachilidae, three species from Halictidae, and six wild bee species from Apidae family.

In the Ridge Gourd, the Shannon diversity index was 1.94 and Shannon evenness index was 0.3, *Apis florea* was the most abundant species with 23.48%, followed by *Apis dorsata* (21.25%) and *Tetragonula iridipennis* (17.83%). *Amegilla zonata* (0.74%) and *Megachile lanata* (0.3%) were rare visitors of ridge gourd flower. *Apis* bees were the most dominant visitors of ridge gourd flower followed by *Nomia elliotii* of Halictidae family, bees from subfamily Xylocopinae (*Xylocopa* & *Ceratina* bees) were frequently observed from Apidae family. Among wild bees, *Xylocopa fenestrata* and *Nomia elliotii* were dominant throughout the survey in both the crops.

Patricio et al. (2012) recorded the role of bees as

Table 1. List and abundance of the bee species individuals encountered during the survey of Brinjal and Ridge Gourd fields.

Order	Family	Species	Brinjal	Ridge Gourd	Total
Hymenoptera	Apidae	*Apis dorsata* Fabricius, 1793	8	143	152
		Apis cerena Fabricius, 1793	10	49	59
		Apis florea Fabricius, 1787	24	158	182
		Tetragonula iridipennis Smith, 1854	142	120	262
		Xylocopa fenestrate Fabricius, 1798	38	25	63
		Xylocopa aestuans Linnaeus, 1758	7	16	23
		Xylocopa magnifica Cockerell, 1929	0	8	8
		Xylocopa sp.	3	0	3
		Ceratina smaragdula Fabricius, 1787	0	39	39
		Ceratina hieroglyphica Smith, 1854	5	0	5
		Amegilla zonata Linnaeus, 1758	16	5	11
		Amegilla calceifera Cockerell, 1911	13	0	13
	Halictidae	*Nomia elliotii* Smith, 1875	61	108	169
		Nomia crassipes Fabricius, 1798	22	0	22
		Nomia westwoodi Gribodo, 1894	7	0	7
	Megachilidae	*Megachile lanata* Fabricius, 1775	62	2	64
		Megachile hera Bingham, 1897	3	0	3

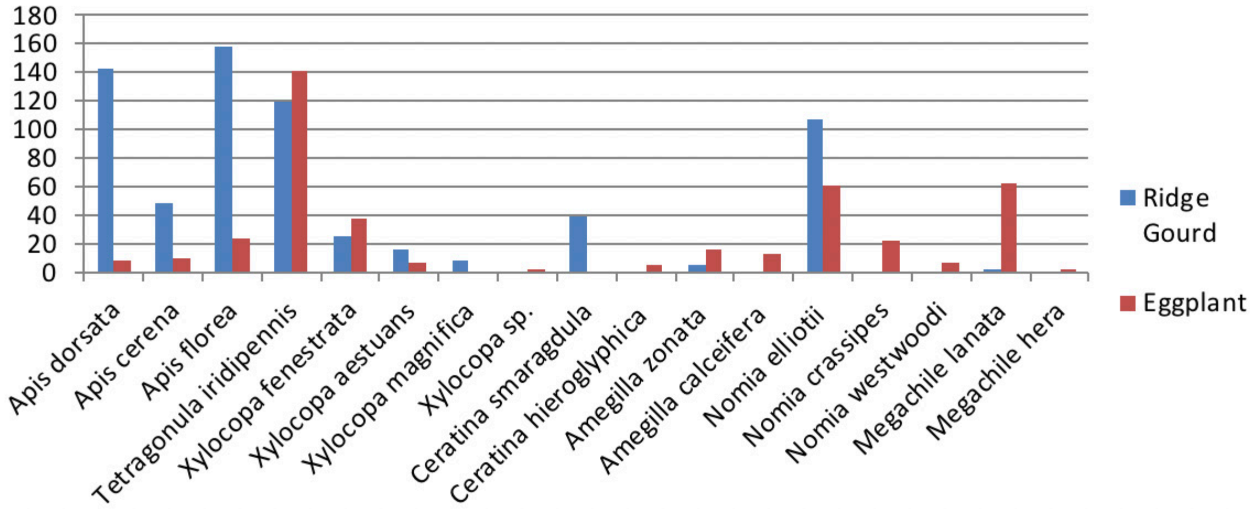

Figure 2. Relative abundance of bees in Ridge Gourd and Brinjal crop fields, where Y axis indicates individual number of bee species & X axis indicates bee species.

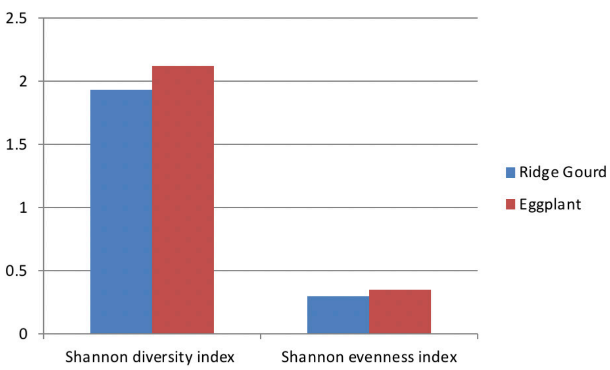

Figure 3. Shannon diversity index & Shannon evenness index of bee species in the Ridge Gourd & Brinjal crop fields.

very significant in promoting good yields in Brinjal. Our results exhibit that stingless bees *Tetragonula iridipennis* are effective pollinators for both the crops in fields and similar results observed in greenhouses by Silva et al. (2013). In an earlier study, Herren & Ochieng (2008) observed that *Xylocopa caffra* was an effective pollinator of Brinjal crop and its visitation rates significantly reduces with the distance from wild habitat. Land management is one of the factors which determines the efficiency of pollination in agriculture (Patricio et al. 2012) as flowers of wild plants was important foraging source for bees. Agro-ecosystem, close to high proportion of natural habitat is benefited by bee diversity, foraging movement, and their mutualistic behavior (Hagen & Kraemer 2010; Balachandran et al. 2017). Agroforestry not only provides niche diversity, it also reduces pest problems (Stamps & Linit 1998).

Conclusion

The experimental study proves that there is a great diversity and abundance of non *Apis* bee species along with *Apis* bee species present in Brinjal and Ridge Gourd fields, as surrounding natural habitat provide them alternative habitat and floral resources which enhance the diversity and population of wild bees.

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NAAS rating (India) 5.64

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OPEN ACCESS

www.threatenedtaxa.org

ISSN 0974-7907 (Online) | ISSN 0974-7893 (Print)

March 2023 | Vol. 15 | No. 3 | Pages: 22771–22926
Date of Publication: 26 March 2023 (Online & Print)
DOI: 10.11609/jott.2023.15.3.22771-22926

Article

Communications

Short Communications

Notes

Publisher & Host

Threatened Taxa