

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50

Bees support farming. Does farming support bees?

Preeti S. Virkar^{1¶*}, Ekta Siddhu^{2&}, V. P. Uniyal³

¹ Department of Zoology, North Eastern Hill University, Shillong, Meghalaya, India

² PGT Biology, Oak Grove School, Dehradun, Uttarakhand, India

³ Landscape Level Planning and Management, Wildlife Institute of India, Dehradun, India

* Corresponding author

E-mail: preetivirkar85@gmail.com

¶ This author contributed equally to the work

& This author also contributed equally to the work

51 **Abstract**

52 Tropical regions are subjected to rapid land use changes altering species
53 composition and diversity in communities. The non-*Apis* bees are vital invertebrates
54 continued to be highly neglected in the tropics. We compared their diversity status,
55 richness and composition across natural areas and agroecosystems in Doon valley, a
56 subtropical-temperate landscape situated at the foothills of outer Himalayas in India. We
57 investigated how two major habitats relate to non-*Apis* bee diversity, specifically seeking
58 answers to (1) Whether natural habitat is a refuge to richer and rarer bee communities
59 than agroecosystems? (2) Are natural habitats important for supporting wild bee
60 populations in agroecosystems? (3) Do polyculture farms behave similar to natural
61 habitats and therefore support richer bee communities than monoculture? Observation and
62 pantrap sampling were used to collect data. We recorded 43 species belonging to bees of
63 five families. The findings of our investigation demonstrate the importance of natural
64 habitats as a potential refuge for non-*Apis* bees. The findings highlighted that Doon valley
65 harboured twenty-five rare species of non-*Apis* bees, and natural habitats are a refuge to
66 11 rare specialist species (clamtest; Specialization threshold $K = 2/3$, Alpha level =
67 0.005). Natural habitat diversity in Doon valley supports bee communities in nearby
68 agroecosystems ($R^2 = 0.782$, $SE = 0.148$, $P = 0.004$). Polyculture practices in
69 agroecosystems (<100m from forest $H' = 2.15$; >100m from forest = 2.08) in the valley
70 mimic natural habitats ($H' = 2.37$) and support diverse non-*Apis* bee communities (2.08)
71 in comparison to monocultures (<100m from forest $H' = 2.13$; >100m from forest = 1.56).
72 Bees evolved with flowering plants over 120 million years and they suffice an ever-
73 growing anthropogenic nutrition needs with their services through enhanced agricultural
74 production in pursuit of forage. We finally recommend similar assessments of bee
75 diversity and plants they support in different habitats and vice versa.

76 **Introduction**

77 Pollinators have a crucial role to play in pollination, a key ecological service, that
78 enhances plant production [1,2]. Bees, in particular, are considered the prime pollinator
79 group [3,4]. Beekeeping has hence become an indispensable part of farming cultures
80 worldwide. Managed honey bees successfully pollinate and are responsible for the
81 production of seeds and fruits of about 75% of the most commonly consumed food crops
82 worldwide [5] and an unknown number of wild plants globally [1,2,5]. In addition to the
83 managed honey bees, pollination by the native wild bees is an indiscernible but
84 imperative process to the ecosystem. Native wild bees (non-*Apis*) other than honey bees
85 (*Apis*) are increasingly finding the center stage in the backdrop of the global decline of
86 the managed bees [6,7]. Over the last half a decade the honey bee populations suffered a
87 massive decline globally, predominantly in North America [8,9] and a Europe [10,11],
88 leading to pollinator crisis [12].

89 There are several reasons for the bee decline such as climate change [13,14],
90 pollution, pesticide usage [15,16], introduction of exotic species [17,18], electromagnetic
91 waves from mobile towers [19], and pathogens, [20] etc. Changing climate and land use
92 are among the prime drivers of pollinator decline degrading their habitats. Conversion of
93 additional natural land for agriculture is a significant cause of pollinator habitat
94 degradation [21]. It alters biodiversity [22,23], and is predicted to be one of the leading
95 causes of species loss in the future owing to anthropogenic modifications in the global
96 environment [24–26], particularly in the tropics. Tropical regions sustain rare and
97 endemic species of plants, animals and their ecosystem services. Owing to lack of
98 exploration and documentation, the discovery of many species may be yet remaining.
99 There is limited baseline information on the status of non-*Apis* bees in the changing
100 tropical and subtropical landscapes [27].

101 The global human population is estimated to reach nine billion by 2050 [28,29].
102 Catering to the nutritional needs of a rapidly growing population will mean the
103 conversion of natural habitats to agriculture [30]. Over the past twenty-five years (from
104 1990-2015) 129 million ha of natural land were lost to agriculture worldwide [31].
105 Tropical and developing countries such as India have undergone much rapid land cover
106 conversions. From 1880-2010 the land use land cover (LULC) in India the forests cover
107 decreased by 34% (134 million ha to 88 million ha) while the agricultural land increased
108 by 52% (92 million ha to 140 million ha) [32]. Studies demonstrate that natural habitats
109 are reservoirs of resources required by bees that may be absent in agroecosystems [7,33–
110 36]. Forest cover reduction and farmlands gaining vegetation uniformity with increasing
111 monoculture cause the loss of nesting and foraging sites of the bee pollinators [37,38].
112 Studies on semi-natural habitats have shown to differentially support bee populations in
113 agricultural landscapes [39,40]. Pollinators' utilize forest and agrarian habitats for
114 resources such as forage and nesting [22,41–44]. Monoculture reduces not only natural
115 areas [45] in and around farms but also the floral diversity [38]. The recent bee falloff is
116 attributed to increased conventional monoculture agricultural practices that reduce
117 wildflower abundance [16,46–49]. These practices upset the plant-pollinator community
118 structure [14] and function [50]. Agricultural intensification is an critical global change
119 presently leading to local and global consequences such as poor biodiversity, soil
120 depletion, water pollution and eutrophication and atmospheric components [51]. It can
121 negatively affect the insect pollination services, and thus, decreasing the production of
122 66% crops impacting the global nutrition supply [52]. In the wake of such information,
123 one wonders what kind of differences agriculture and natural habitat might bring to bee
124 diversity.

125 The Himalayan ecosystem is one of the global biodiversity hotspots. It is
126 gradually falling prey to alterations in climate and land cover, to support growing
127 economic needs. These very causes are affecting bee populations worldwide as well, and
128 the Himalayas are particularly sensitive to them [53–56]. Rising temperatures influence
129 plant reproduction and phenology. Mismatch of the plant life cycle will, in turn, affect the
130 pollinators [13,57–59]. Understanding the ecosystem services in the Himalayas has begun
131 [60]. The Global Pollination Project, in particular, investigated the contribution of insect
132 pollinators to the productivity of important crops such as oilseeds, fruits and spices
133 cultivated in the Indian Himalayas [61].

134 Himalayan agriculture is dependent on the managed pollinators for crop
135 productivity. A secondary economic source through honey production is an age-old
136 practice in these mountains [62–65]. The introduction of the non-native honey bees,
137 increasing anthropogenic pressures on the natural resources, climate and lifestyle
138 alterations are further challenging the traditional beekeeping in the region. Few
139 investigations revealed honey bee declines reported in the Himalayan ecosystems [62,65–
140 68]. The rate of honey bee decline in the region and South Asia on a broader scale is
141 unknown. This gap points out the need for utilizing the services of non-*Apis* bees to
142 improve the reproduction in the wild and cultivated Himalayan plants. Lack of
143 comprehensive investigation and historical records on non-*Apis* bees is a hindrance
144 towards understanding their ecological function and economic potential in the region.
145 Doon valley is a mosaic of natural, agricultural and human habitats, situated at the
146 foothills of the outer Himalayas. Demonstrating both, traditional chemical-free temperate
147 mountain farming and the conventional intensive cultivation from the Gangetic plains,
148 this Himalayan valley is a perfect example of the changing Himalayan LULC. Few
149 studies in the recent past that have looked at the insect pollinators in Doon valley. Jiju et

150 al [69] recorded pollinators and flower visitors viz. Dipterans (n= 7), Hymenopterans
151 (honey bees n=3-, wasp n=1-), Coleopterans (n=3), Hemipterans (n=1) and Lepidopterans
152 (n=4) in an organic farm. This investigation, however, lacked any records of non-
153 *Apis* bees. Migrating human populations from the mountains and the plains are causing
154 rapid land use alterations affecting diverse faunal species in the Doon valley (Yang et al.
155 2013). Transitional climatic conditions and geography make the Doon valley a unique
156 landscape ideal for supporting a potential source population of non-*Apis* bees for the
157 surrounding areas. We investigate how two major habitats of LULC viz. natural and
158 agriculture in the Doon valley landscape, affect non-*Apis* bee diversity, specifically
159 seeking answers to (1) Whether natural habitat is a refuge to diverse and rarer bee
160 communities than the agroecosystems? (2) Are natural habitats important for supporting
161 wild bee populations in agroecosystems? (3) Do polyculture farms behave similarly to
162 natural habitats, thus support species-rich and diverse bee communities than
163 monoculture?

164

165 **Methods**

166 **Study Area**

167 Doon valley (latitudes 29°59' to 30°30' N and longitudes 77°35' to 78°24' E) is
168 situated in the western corner of Uttarakhand state, India (Fig 1). It is spread over
169 approximately 1850 km² area with the elevation ranging from 330 m to 800 m above
170 mean sea-level. The valley is a mosaic of natural habitats such as forest patches, seasonal
171 and perennial riverine systems, agriculture land and urban settlements (Fig 2 and Table
172 1). Situated at the foothills of the Himalayas, the valley is sandwiched between the
173 Shivalik ranges. The rivers Ganga and Yamuna mark the south-eastern and north-western

174 boundaries of the valley, respectively. Doon valley is a fragile, tectonically active
175 landscape with a climate ranging from sub-tropical to temperate type. Ecologically, the
176 valley forms a landscape-level ecotone between the hot tropical plains and the temperate
177 Himalayan mountain ecosystems. Traditionally, the farming practice consists of multiple
178 crops in different seasons of cultivation *viz.* Kharif, Jayad and Rabi. The major groups of
179 crops grown consist of cereals (wheat, paddy, maize, and millets), oilseeds (mustard,
180 sesame, and linseed), vegetables (potato, tomato, brinjal, radish, cabbage, okra, pea,
181 onion, capsicum, French bean, ginger, garlic) and cash crops (sugarcane)[70]. The valley
182 is famous for its variety of rice called Dehradun Basmati [71]and fruit orchards of litchi
183 [72]. Other fruit orchards commonly cultured in the valley are pear, mango, guava, peach
184 and Indian gooseberry. Numerous local citrus varieties and vegetables are grown
185 seasonally in the valley for household consumption [70]. Based on the increasing
186 demands and economic benefits, crops such as wheat and sugarcane are taking over the
187 diverse cropping system in the Himalayas [73]. One can find many monocultures and
188 polycultures in the valley based on the type and scale of farming.

189

190 **Fig 1. Sampling locations for bee species in Doon valley, India.**

191 **Fig 2. Land use and land cover map of Doon valley, India.**

192 **Table 1. Land use and Land cover (LULC) statistics of Doon Valley (in sq. km) in**
193 **2015 (Source: Mishra et al., 2015).**

| LULC Class | Area in % | Area in sq. km |
|------------|-----------|----------------|
| Urban | 39.25 | 1205.37 |
| Water | 1.69 | 52.01 |
| Vegetation | 8.90 | 273.34 |

| | | |
|--------------------|-------|---------|
| Agriculture | 33.12 | 1016.98 |
| Barren Land | 17.04 | 523.29 |

194

195 **Study Design**

196 Since we wanted to compare the bee diversity in natural and agriculture areas, we
197 sampled majorly different types of the habitats mentioned above in Doon valley. The
198 stratified random sampling design was followed in the two habitats (natural- 13500 sq. m
199 and agriculture- 7000 sq. m) across the study site. The minimum radial distance of 1km
200 was maintained between sites within a particular stratum. Sites were chosen such that a
201 50m buffer was left from the edge of the strata. Among the natural habitats, we sampled
202 sal *Shorea robusta* forests, riverine patches and small patches of diverse vegetation
203 (teak *Tectona grandis*, pine *Pinus roxburghii*, bamboo *Bambusa* sp. and derelict
204 tea *Camellia sinensis* plantations). Polycultures and monocultures consisting of food
205 crops and fruit orchards were sampled among the agricultural habitats. We laid 27
206 sampling plots in the natural habitat and 14 plots in the agriculture. The plots were belt
207 transects of 100m×5m with five subsampling plots of 5m×5m dimension. The study site
208 consisted of 203 subsampling plots in the natural (Sal- 45, riverine- 60 and
209 miscellaneous-30) and agricultural (polyculture- 33, monoculture- 35) habitats. The
210 sampling was carried out in the peak flowering periods. Three replicates were repeated
211 from February to May in 2012, January to May 2013 and 2014.

212 **Bee Sampling and Identification-** Bees were sampled using active and passive methods on
213 each transect. The active methods included visual observations using a transect walk and
214 net sweeping. Visual observations were performed with a walk along the length of the
215 transect searching for bees up to 2m on either side. Any sightings beyond this distance
216 were ignored. It took approximately 20 minutes to complete one transect walk. Three

217 temporal replicates of the transect walk were taken from 600 to 800 hrs., 1200 to 1400
218 hrs. and 1600 to 1800 hrs. Species unidentifiable in the field were collected using insect
219 nets for further identification. The passive method comprised of the use of coloured
220 pantraps to collect bees that are attracted to flower colours [74–77]. A set of three colours
221 of plastic pantraps were used: yellow, blue and white [39]. Initially, the pantraps were left
222 for 24 hrs. However, this duration yielded a low number to no bees. Thus, we left these
223 pantraps for 48 hours and collected them on the third day. In total, 1827 pantrap sampling
224 sessions were run (203 traps of three colours with three replicates) throughout the study
225 period across the valley. Bees collected using all the different methods was appropriately
226 curated. Specimens were stored either as a dried specimen and spread in insect boxes or
227 as wet specimen in 70% ethanol vials till further identification. A standard identification
228 key by Michener [4] was referred, to identify bees into families and further. We sorted the
229 specimen into morphospecies as recognizable taxonomic units (RTU) for further data
230 analysis [78–80].

231

232 **Data Analysis**

233 Active sampling resulted in 2799 (Sweep Net=34, Observation=2765) bee records
234 compared to passive (n=432) methods. We pooled the data obtained from both active and
235 passive sampling to assess the species diversity of bees across different families. We
236 calculated the bee species richness for all the habitats using non-parametric estimators
237 (Colwell and Coddington 1994). We computed the Bray-Curtis dissimilarity index to
238 examine whether bee species composition in the two primary habitats varied in Doon
239 valley using Analysis of Similarity (ANOSIM) [81,82]. A non-metric multidimensional
240 scaling (NMDS) ordination was performed on the rank orders of dissimilarity values
241 obtained from the ANOSIM. We encountered honey bees frequently (n = 2468) compared

242 to non-*Apis* bees (n = 331) in active sampling, suggesting an observation bias towards the
243 former. Hence, we used only pantrap records of bees for the ANOSIM. We performed a
244 multinomial species classification based on species habitat preferences to test the
245 association of bee compositions with natural and agricultural habitats [83]. The data for
246 all the agricultural sampling plots at varying distances from natural habitats was compiled
247 to explore whether natural habitats act as a refuge for bee communities of the
248 agroecosystems. We classified the distance of sampling plot in agriculture from the
249 nearest natural habitats into seven classes. Each distance class was 100 m wide beginning
250 at zero to 700 m. Individual Shannon diversity indices (H') were computed for each of the
251 eight distance classes. We used regression analysis on the Shannon diversity for each
252 distance class to investigate if nearness to natural habitat affects the diversity of bee
253 assemblages in agroecosystems.

254 We wanted to test whether polycultures behave similarly to natural habitats compared to
255 monocultures. For this we measured the Shannon-Weiner diversity of bees across 78
256 subsampling plots from monoculture and polyculture farms near (< 100m) and far from
257 forests or wilderness (> 100m) viz. 20 monocultures near to the forest, 20 monocultures
258 far from the forest, 18 polycultures close to forest and 20 polycultures far from forest. We
259 compared the farm Shannon-Weiner diversity values with that of the different forests
260 combined.

261 The analyses were carried out in the program R version 3.3.1 using package
262 "vegan"[84,85].

263

264 **Results**

265 We recorded 3231 (432 in pantraps, 2799 through observation samplings)
266 individual adult female bees. These individuals belonged to 43 species of bees falling in

267 five families and 17 genera (Table 2). There were thirty-nine non-*Apis* and
 268 four *Apis* (*Apis indica*, *A. florea*, *A. mellifera* and *A. dorsata*) bee species.

269 **Table 2. List of bees from Doon Valley**

| No. | Family | Bee Species | Agriculture habitat | Natural habitat |
|-----|------------|---------------------------------|---------------------|-----------------|
| 1 | Andrenidae | <i>Andrena Euandrena</i> sp. 3 | + | + |
| 2 | Andrenidae | <i>Andrena Euandrena</i> sp. 4 | + | + |
| 3 | Andrenidae | <i>Andrena flavipes</i> | + | + |
| 4 | Andrenidae | <i>Andrena</i> sp. 2 | + | + |
| 5 | Andrenidae | <i>Andrena</i> sp. 3 | + | - |
| 6 | Andrenidae | <i>Andrena Zonandrena</i> sp. 1 | + | + |
| 7 | Andrenidae | <i>Andrena</i> sp. 4 | + | + |
| 8 | Andrenidae | <i>Andrena</i> sp. 1 | + | + |
| 9 | Apidae | <i>Amegilla zonata</i> | - | + |
| 10 | Apidae | <i>Anthophora</i> sp. 2 | - | + |
| 11 | Apidae | <i>Anthophora</i> sp. 1 | - | + |
| 12 | Apidae | <i>Apid</i> sp. 1 | - | + |
| 13 | Apidae | <i>Apis dorsata</i> | + | + |
| 14 | Apidae | <i>Apis florea</i> | + | - |
| 15 | Apidae | <i>Apis indica</i> | + | - |
| 16 | Apidae | <i>Apis mellifera</i> | + | + |
| 17 | Apidae | <i>Bombus haemorrhoidalis</i> | + | + |
| 18 | Apidae | <i>Ceratina smaragdula</i> | + | + |

| | | | | |
|----|--------------|-----------------------------|---|---|
| 19 | Apidae | <i>Ceratina</i> sp. 5 | - | + |
| 20 | Apidae | <i>Ceratina</i> sp. 2 | - | + |
| 21 | Apidae | <i>Ceratina</i> sp. 3 | + | + |
| 22 | Apidae | <i>Ceratina</i> sp. 4 | - | + |
| 23 | Apidae | <i>Colletid</i> sp. 1 | + | + |
| 24 | Apidae | <i>Tetragonula</i> sp. 2 | + | + |
| 25 | Apidae | <i>Tetragonula</i> sp. 1 | - | + |
| 26 | Apidae | <i>Xylocopa astuens</i> | + | + |
| 27 | Apidae | <i>Xylocopa</i> sp. 1 | + | + |
| 28 | Halitidae | <i>Halictid</i> sp. 4 | - | + |
| 29 | Halitidae | <i>Halictid</i> sp. 1 | + | + |
| 30 | Halitidae | <i>Halictus</i> sp. 2 | + | + |
| 31 | Halitidae | <i>Halictus</i> sp. 3 | + | + |
| 32 | Halitidae | <i>Lasioglossum</i> sp. 2 | + | + |
| 33 | Halitidae | <i>Lasioglossum</i> sp. 1 | - | + |
| 34 | Halitidae | <i>Nomia interstitialis</i> | + | + |
| 35 | Halitidae | <i>Nomia</i> sp. 1 | + | + |
| 36 | Halitidae | <i>Nomia wetwoodi</i> | + | - |
| 37 | Halitidae | <i>Patellapis</i> sp. 1 | - | + |
| 38 | Halitidae | <i>Sphecodes</i> sp. 1 | + | + |
| 39 | Megachilidae | <i>Megachile lanata</i> | - | + |
| 40 | Megachilidae | <i>Megachile</i> sp. 1 | - | + |
| 41 | Megachilidae | <i>Megachile</i> sp. 9 | - | + |
| 42 | Megachilidae | <i>Megchile</i> sp. 8 | - | + |

| | | | | |
|----|--------------|-------------------|---|---|
| 43 | Megachilidae | <i>Osmia adae</i> | + | + |
|----|--------------|-------------------|---|---|

270

271 The species composition of bees was significantly more similar within habitats
 272 than between habitats (R statistic = 0.20, p = 0.004) (Table 3). Bee composition in
 273 agroecosystems slightly overlapped with the different natural habitats. We pooled the data
 274 for the different natural habitats and overlaid it on that of agroecosystems. We found that
 275 arable lands shared the majority of the species with the different natural habitats in the
 276 Doon valley (Fig 3).

277 **Fig 3. Species composition of bees in different habitats in Doon valley constructed**
 278 **using Nonmetric Multidimensional Scaling.** Overlay of bee communities between
 279 agroecosystems (green polygon) and different types of forest habitats (blue, orange, &
 280 red). Forest habitats pooled together (black polygon).

281 **Table 3. Comparison of bee community similarity between forest (Riverine Forest-**
 282 **RF, Sal Forest- SF and Miscellaneous vegetation- MIS) and agroecosystems (AGR)**
 283 **habitats in Doon valley (Pair wise ANOSIM, p<= 0.05).** (Values above and below
 284 diagonal are R and p values respectively).

| | | | |
|------------------|------------------|-------------------|-------------------|
| <i>RF</i> | 0.33 | 0.09 | 0.23 |
| 0.006 | <i>SF</i> | 0.22 | -0.01 |
| 0.07 | 0.007 | <i>AGR</i> | 0.01 |
| 0.05 | 0.46 | 0.409 | <i>MIS</i> |

285

286 We classified the bees into habitat (agriculture, forest) specialists, generalists and
287 species too rare to be classified with confidence (Fig 4). Of the total bee species, 58.14%
288 were rare (n= 25), 25.58% (n= 11) were forest specialists, and 9.3% (n= 4) were
289 generalists and found in both the habitats. During sampling three bee species (6.98%) viz.,
290 Dwarf bee (*Apis florea*), Asiatic honey bee (*Apis indica*), and *Andrena* sp. three were
291 detected only in the agricultural habitats. It is interesting to note that these species were
292 observed inhabiting edges and interiors of the forests in the vicinity of the
293 agroecosystems. Hence, these species are not specialists to agroecosystems but use both
294 the habitats for foraging and nesting and may be subjective to availability of different
295 resources year-round.

296 **Fig 4. Species classification into specialists (agricultural and forest habitats) and**
297 **generalists in Doon valley (Specialization threshold $K = 2/3$, Alpha level = 0.005).**

298 Bee diversity was significantly higher in agroecosystems in close proximity to
299 forests (H' for <200 m = 1.60) compared to those further away (H' for >600 m = 0.56)
300 ($R^2 = 0.782$, $SE = 0.148$, p value= 0.004) (Fig 5).

301 **Fig 5. Influence of natural habitat on bee community richness in agroecosystems**
302 **(linear regression model; $R^2 = 0.782$, $SE = 0.148$, $P = 0.004$).**

303 Our results demonstrate that forests harboured the highest number of bees (n=21),
304 followed by polycultures near forests or wilderness (n=19) and monoculture near the
305 forest (n=15), polyculture away from the forest (n=13) and monocultures away from the
306 forests (n=9). The Shannon-Weiner diversity of forests was 2.37, monocultures near
307 forests were 2.13, polycultures near forest was 2.15, monocultures away from forest were
308 1.55 and polycultures away from the forest was 2.08. The bee community diversity
309 between monocultures and polycultures close to the forests were similar than those farther

310 away. Polycultures supported a diverse bee community than monocultures that were away
311 from the forests (Table 4).

312 **Table 4. Shannon-Weiner diversity of bee communities in forests, monocultures and**
313 **polycultures across Doon Valley, India.**

| Habitat | Shannon-Weiner diversity | Species Richness |
|-------------------------------------|---------------------------------|-------------------------|
| Monoculture away from forest | 1.55 | 9 |
| Monoculture near forest | 2.13 | 15 |
| Polyculture away from forest | 2.08 | 13 |
| Polyculture near forest | 2.15 | 19 |
| Forests | 2.37 | 21 |

314

315 **Discussions**

316 Continual land use changes to meet the needs of a growing human population are
317 predicted to be the primary drivers of species decline [24], including essential pollinators
318 such as bees [21]. The status of the vast majority of non-*Apis* bees remains uncertain
319 owing to inadequate exploration. Honey bees, on the contrary, form only a small portion
320 and yet have gained more considerable attention and become exhaustively studied. We
321 attempt to bridge this gap and investigate the role of changing land use in shaping the
322 non-*Apis* bee communities in a fragile river valley landscape at the foothills of the
323 Himalaya. Ours is the first study on bees of this region and may be used as baseline
324 evidence to compare future patterns in their communities locally. We found that Doon
325 valley harbours 6.3% of the 678 bee species recorded from the Indian sub-continent [86].

326 Our investigation pointed out that a majority of these species consist of the less explored
327 non-*Apis* bees (90.7%). Various bee researchers have demonstrated that honey bees
328 (genera *Apis*) are a tiny fraction of the vast majority of bees described from the world
329 over [4,87]. It is not surprising that the Doon valley demonstrates a similar pattern of the
330 bee biodiversity. Many (n = 30) bees recorded in the present study (n = 43) are segregated
331 into morphospecies and are yet to be identified up to species level. Using specific
332 taxonomic keys for bees may increase the total number of species in India.

333 We found that bee composition within habitats demonstrated more significant similarity
334 than between habitats in Doon valley. Interestingly, the bee composition of the
335 agroecosystems was a subset of the natural habitats. Bees require a diverse habitat with
336 resources for breeding, nesting, and foraging to complete their life cycles. All the
337 resources required may be unavailable within the habitats that bees occupy. For example,
338 some bees depend on particular plant pollen for proteins that may be highly nutritious for
339 reproduction [88]. However, flowers with such protein-rich pollen may not bloom year
340 around always, which makes them move from one habitat patch to another.
341 Agroecosystems are abundant sources of mass flowering and may serve as a food support
342 system for bees at a particular time of the year. Thus, numerous bees utilize both natural
343 and human-managed ecosystems such as cropland to suffice their nutritional, sheltering
344 and their reproduction requirements [22,41,43,44,88]. We sampled the bees in the peak
345 flowering period in Doon valley. During this is the period many farms in the valley have
346 abundant vegetables, fruits and oilseed plants in the various stages of flowering. Although
347 most bees nested in different natural habitats, agroecosystems may act as rich foraging
348 grounds for some species during the spring in the valley. Thus, the bee composition of
349 agroecosystems overlapped partially with that of the natural habitats in the valley.

350 Our study highlighted that more than half of the bees in the valley were rare. Patterns of
351 the rarity of bees through a large number of singletons reported may arise because of
352 under-sampling, an unrecognized universal trait of a rarity in communities or existence of
353 transient species that thrive well in other regions [89]. Williams et al. [89] tried to
354 understand the change in bee communities across the globe. They highlighted that the
355 native bee community are highly diverse and rich in rare species at local scales (due to a
356 large number of singletons at such scales). Several other researchers reported this pattern
357 in various studies across regions [90–94]. We sampled the valley in peak flowering
358 season, which may answer a part of the question of a rarity in species due to under-
359 sampling during other seasons. Considering that Doon Valley is a transition between two
360 different ecosystems, the other two possibilities of a large number of a rarity in
361 communities based on a universal pattern and transient species cannot be ruled out.

362 Over one-fourth of the bees, we recorded from the valley preferred natural habitats of the
363 forests. Few generalist species were found in both the habitats. Interestingly, 3 of the bee
364 species viz. Dwarf bee (*Apis florea*), Asiatic honey bee (*Apis indica*), and *Andrena* sp. 3)
365 were classified to prefer agroecosystems. *Apis florea* prefers bushy shrubs with strong
366 twigs to make their nests. Thus, they are highly sensitive to incidences, such as fires.
367 Forest fires are frequent in the valley from mid to end of the spring. Activities such as
368 leftover cigarette buds discarded by humans venturing into the forests for extracting
369 fodder and firewood usually trigger forest fires. They are intensified further by the dry
370 season. Hence, farm boundaries and hedgerows form favourable spaces for the dwarf bees
371 to build their nests beside the availability of abundant food in the spring. The Asiatic
372 honey bees are generalist feeders and feed in large numbers in farmlands with abundant
373 flowering crops. One can observe these bees foraging in large numbers on mustard and
374 other flowering crops in Doon valley in the spring. During different seasons these bees

375 are seen foraging on a diversity of wild and cultivated plants. They reside in parallel
376 combs similar to their close cousins, the *Apis mellifera* in hollows of trees, rocks or
377 undisturbed enclosed spaces in case of urban areas. Finding *A. indica* hives in farmlands
378 are rare unless there are intact patches of large trees with hollows or rocky patches.
379 Forests are suitable and typical habitats to find these bees. *Andrena* bees nest on well-
380 drained, steep open banks [95]. Field boundaries that are used to segregate different crops
381 in Doon valley provide such habitats in abundance. Morandin et al. [40] reported similar
382 observations in their study where untilled field margins adjoining roads provided suitable
383 habitats for *Andrena* bees to nest. Hence, these three species should be treated as
384 facultative rather than specialists as they utilize resources from both the forests and the
385 agroecosystems.

386 Agroecosystems at increasing distances from the natural habitats demonstrated lower bee
387 diversity in our study. Numerous studies in the past reported similar findings. Pollinators
388 depend on natural and semi-natural habitats adjacent to agroecosystems for supplemental
389 food resources and shelter [6,96–98]. Wild bees in forests demonstrate limited foraging
390 ranges. The valuable services of these bees influence agroecosystems in the vicinity of
391 forests [7]. Maintaining natural habitats within or surrounding the agroecosystems crucial
392 for wild bee pollination services [99].

393 Our results illustrate that monocultures close to forest ecosystems show diverse bee
394 communities than those farther away. Surprisingly, the bee richness in polycultures away
395 from the forests was similar to monocultures in close vicinity of the forests. Our results
396 demonstrate that polycultures behave similar to natural habitat in conserving bees. The
397 outcomes of our study indicate that polyculture farms had rich bee species compared to
398 monoculture. Earlier studies (Potts et al. 2003) showed that bee communities are
399 positively linked to floral diversities and prefer polyculture over monoculture [100]. The

400 traditional Himalayan agriculture consists of diverse crops [101]. Polyculture systems that
401 we sampled consisted of different crops in combinations of 2 to 4 species and wildflowers
402 on the bunds to segregate them, which may have supported a rich composition of bees.
403 On the contrary, our study recorded fewer bee species in monocultures of wheat
404 (*Triticum* spp.) and mustard (*Brassica juncea* (L.) Czern). Wheat is wind-pollinated and
405 does not provide biotic pollinating agents with rewards such as nectar and pollen. In
406 monoculture, we found most bee species on mustard or on wild invasive plants such
407 as *Lantana camara* and *Ageratum conyzoides* that grew on the boundaries of the farms.
408 Polycultures have a greater diversity of native plants than monocultures which influences
409 the bee biodiversity in agroecosystems [102]. Our findings demonstrate that forests are
410 reservoirs of diverse bee communities in adjoining patches of agroecosystems. The
411 present analysis supports the fact that polycultures act as reservoirs of habitat to bees
412 compared to monocultures in close vicinity to natural habitats.

413

414 **Conclusions**

415 Our investigation on bees in Doon valley, a landscape with gradual changing
416 LULC at the foot of the Himalaya, is the first one to document the bees (*Apis* and non-
417 *Apis*) in the forest and agricultural habitats of the region. Our findings demonstrate that
418 the Doon valley landscape and its natural habitats are a refuge to a diverse community of
419 rare and specialist bees. Agroecosystems shared a lot more species in common with each
420 of the natural habitats. Forests and wilderness are essential habitats to support diverse bee
421 communities in and around the agroecosystems. Furthermore, polycultures support higher
422 bee diversities over monoculture practices. Wilderness along field boundaries such as
423 hedges stands as connectivity between different habitats. Monoculture expansions have

424 diminished these vital corridors [38,103,104], affecting the survival of pollinators [45].

425 Our study implies the importance of multi-crop farming and preserving as many natural

426 habitats as possible to attract native bees and benefit both cultivated and wild plant

427 production.

428 The global tree cover shows an increase of 7% (2.24 million sq. km) from 1982 to 2016

429 (Song et al. 2018), differing from a previous assessment claiming loss of forest (FAO

430 2015). India was ranked first in short vegetation gain (270,000 sq. km), most of which

431 can be attributed to the agricultural intensification under the green revolution [105].

432 Extension of land under intensive agrarian practices is a prime cause of deforestation and

433 loss of wilderness habitats. Wilderness play buffers to biodiversity that have lost intact

434 natural habitats. Loss of wilderness causes the extinction of several terrestrial species

435 across the global biogeographic realms, including the Indomalayan region [106]. Loss of

436 wilderness habitats comprising of essential resources can drive local pollinators

437 depending on them to extinction. Our investigation highlights that natural habitats are

438 integral to bee diversity. In the milieu of honey bee decline worldwide Polycultures give

439 some hope to non-*Apis* bee diversity in a Himalayan valley landscape. Thus, there is a ray

440 of hope to “land sharing and sparing” as Baurdon and Giller to feed a growing population

441 [107]. Using ecologically friendly farming such as polycultures nutritious biodiverse

442 food for a growing population can be produced while conserving wild pollinators

443 simultaneously. An assessment on similar lines is needed to understand bee diversity

444 occupying natural and arable habitats in the tropical and sub-tropical regions of the world.

445 Besides, it is crucial to understand what percentage of these bees support crop production

446 and do our present agricultural practices in return support bees?

447

448 **Acknowledgements**

449 We are grateful to the Director, Wildlife Institute of India, Director and Staff of
450 Dehradun Forest Division, Uttarakhand. We thank the Department of Entomology, Indian
451 Agricultural Research Institute, New Delhi for the guidance and identification of the
452 specimen. We would like to extend our gratitude to Research Foundation for Science,
453 Technology and Ecology, Navdanya Trust, New Delhi for their support to work with
454 farmers. We are grateful to the State Biotechnology Department, Government of
455 Uttarakhand, India. (SBD/R&D/01/11/02-87) for funding the study. We are indebted to
456 the farmers in Doon valley for their cooperation in letting us conduct uninterrupted field
457 work for the study.

458

459 **References**

- 460 1. Aguilar R, Ashworth L, Galetto L, Aizen MA. Plant reproductive susceptibility to
461 habitat fragmentation: Review and synthesis through a meta-analysis. *Ecol Lett.*
462 2006;9: 968–980. doi:10.1111/j.1461-0248.2006.00927.x
- 463 2. Ashman T-L, Knight TM, Steets JA, Amarasekare P, Burd M, Campbell DR, et al.
464 Pollen Limitation of Plant Reproduction: Ecological and Evolutionary Causes and
465 Consequences. *Ecology.* 2004;85: 2408–2421. doi:10.1890/03-8024
- 466 3. Michener CD. Biogeography of the Bees. *Ann Missouri Bot Gard.* 1979;66: 277–
467 347.
- 468 4. Michener CD. *The Bees of the World.* Baltimore, Maryland: The John Hopkins
469 University Press; 2007.

- 470 5. Klein A-MM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA,
471 Kremen C, et al. Importance of pollinators in changing landscapes for world crops.
472 Proc R Soc B Biol Sci. 2007;274: 303–313. doi:10.1098/rspb.2006.3721
- 473 6. Kremen C, Williams NM, Thorp RW. Crop pollination from native bees at risk
474 from agricultural intensification. Proc Natl Acad Sci. 2002;99: 16812–16816.
475 doi:10.1073/pnas.262413599
- 476 7. Ricketts TH. Tropical Forest Fragments Enhance Pollinator Activity in Nearby
477 Coffee Crops. Conserv Biol. 2004;18: 1262–1271. doi:10.1111/j.1523-
478 1739.2004.00227.x
- 479 8. National Research Council. Status of Pollinators in North America. National Acad
480 Press. National Academies Press; 2006.
- 481 9. vanEngelsdorp D, Meixner MD. A historical review of managed honey bee
482 populations in Europe and the United States and the factors that may affect them. J
483 Invertebr Pathol. 2010;103: S80–S95. doi:10.1016/j.jip.2009.06.011
- 484 10. Potts SG, Roberts SPM, Dean R, Marris G, Brown MA, Jones R, et al. Declines of
485 managed honey bees and beekeepers in Europe. J Apic Res. 2010;49: 15–22.
486 doi:10.3896/IBRA.1.49.1.02
- 487 11. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global
488 pollinator declines: trends, impacts and drivers. Trends Ecol Evol. 2010;25: 345–
489 353. doi:10.1016/j.tree.2010.01.007
- 490 12. Buchmann SL, Nabhan GP. Forgotten Pollinators. Washington D.C.: Island Press;
491 1996.
- 492 13. Memmott J, Craze PG, Waser NM, Price M V. Global warming and the disruption

- 493 of plant?pollinator interactions. *Ecol Lett.* 2007;10: 710–717. doi:10.1111/j.1461-
494 0248.2007.01061.x
- 495 14. Burkle LA, Marlin JC, Knight TM. Plant-Pollinator Interactions over 120 Years:
496 Loss of Species, Co-Occurrence, and Function. *Science* (80-). 2013;339: 1611–
497 1615. doi:10.1126/science.1232728
- 498 15. Alston DG, Tepedino VJ, Bradley B a, Toler TR, Griswold TL, Messinger SM.
499 Effects of the Insecticide Phosmet on Solitary Bee Foraging and Nesting in
500 Orchards of Capitol Reef National Park, Utah. *COMMUNITY Ecosyst Ecol*
501 *Environ Entomol.* 2007;36: 811–816. doi:10.1603/0046-
502 225X(2007)36[811:EOTIPO]2.0.CO;2
- 503 16. Gilburn AS, Bunnefeld N, Wilson JM, Botham MS, Brereton TM, Fox R, et al.
504 Are neonicotinoid insecticides driving declines of widespread butterflies? *PeerJ.*
505 2015;3: e1402. doi:10.7717/peerj.1402
- 506 17. Traveset A, Richardson DM. Biological invasions as disruptors of plant
507 reproductive mutualisms. *Trends Ecol Evol.* 2006;21: 208–216.
508 doi:10.1016/j.tree.2006.01.006
- 509 18. Thomson DM. Detecting the Effects of Introduced Species : A Case Study of
510 Competition between *Apis* and the effects of introduced of species : a case study
511 Detecting between *Apis* and *Bombus* competition. *Oikos.* 2006;114: 407–418.
512 doi:10.1111/j.2006.0030-1299.14604.x
- 513 19. Favre D. Mobile phone-induced honeybee worker piping. *Apidologie.* 2011;42:
514 270–279. doi:10.1007/s13592-011-0016-x
- 515 20. Cox-Foster DL, Conlan S, Holmes EC, Palacios G, Evans JD, Moran NA, et al. A

- 516 Metagenomic Survey of Microbes in Honey Bee Colony Collapse Disorder.
517 Science (80-). 2007;318: 283–287. doi:10.1126/science.1146498
- 518 21. Bommarco R, Kleijn D, Potts SG. Ecological intensification: harnessing ecosystem
519 services for food security. Trends Ecol Evol. 2013;28: 230–238.
520 doi:10.1016/j.tree.2012.10.012
- 521 22. Kremen C, Williams NM, Aizen MA, Gemmill-Herren B, LeBuhn G, Minckley R,
522 et al. Pollination and other ecosystem services produced by mobile organisms: a
523 conceptual framework for the effects of land-use change. Ecol Lett. 2007;10: 299–
524 314. doi:10.1111/j.1461-0248.2007.01018.x
- 525 23. Tylianakis JM, Tscharntke T, Lewis OT. Habitat modification alters the structure
526 of tropical host–parasitoid food webs. Nature. 2007;445: 202–205.
527 doi:10.1038/nature05429
- 528 24. Sala OE. Global Biodiversity Scenarios for the Year 2100 Science (80-
529). 2000;287: 1770–1774. doi:10.1126/science.287.5459.1770
- 530 25. Larigauderie A, Prieur-Richard A-H, Mace GM, Lonsdale M, Mooney HA,
531 Brussaard L, et al. Biodiversity and ecosystem services science for a sustainable
532 planet: the DIVERSITAS vision for 2012–20. Curr Opin Environ Sustain. 2012;4:
533 101–105. doi:10.1016/j.cosust.2012.01.007
- 534 26. Pereira HM, Navarro LM, Martins IS. Global Biodiversity Change: The Bad, the
535 Good, and the Unknown. Annu Rev Environ Resour. 2012;37: 25–50.
536 doi:10.1146/annurev-environ-042911-093511
- 537 27. Ghazoul J. Buzziness as usual? Questioning the global pollination crisis. Trends
538 Ecol Evol. 2005;20: 367–373. doi:10.1016/j.tree.2005.04.026

- 539 28. United Nations. World Urbanization Prospects The 2007 Revision. Prospects.
540 2008; 1–22. doi:10.2307/2808041
- 541 29. United Nations, UNDESA. World Urbanization Prospects The 2007 Revision
542 Highlights. New York. 2007;ESA/P/WP/2: 883. doi:10.2307/2808041
- 543 30. Tilman D, Fargione J, Wolff B, D’Antonio C, Dobson A, Howarth R, et al.
544 Forecasting Agriculturally Driven Global Environmental Change. *Science* (80-).
545 2001;292: 281–284. doi:10.1126/science.1057544
- 546 31. Food and Agriculture Organization. Global Forest Resources Assessment 2015:
547 How are the world’s forests changing? Food Agric Organ United Nations. Rome;
548 2015 Jun. Available: <http://www.fao.org/forestry/fra2005/en/>
- 549 32. Tian H, Banger K, Bo T, Dadhwal VK. History of land use in India during 1880–
550 2010: Large-scale land transformations reconstructed from satellite data and
551 historical archives. *Glob Planet Change*. 2014;121: 78–88.
552 doi:10.1016/j.gloplacha.2014.07.005
- 553 33. Bailey S, Requier F, Nusillard B, Roberts SPM, Potts SG, Bouget C. Distance from
554 forest edge affects bee pollinators in oilseed rape fields. *Ecol Evol*. 2014;4: 370–
555 380. doi:10.1002/ece3.924
- 556 34. Brosi BJ, Daily GC, Shih TM, Oviedo F, Durán G. The effects of forest
557 fragmentation on bee communities in tropical countryside. *J Appl Ecol*. 2007;45:
558 773–783. doi:10.1111/j.1365-2664.2007.01412.x
- 559 35. Gemmill-Herren B, Ochieng’ AO. Role of native bees and natural habitats in
560 eggplant (*Solanum melongena*) pollination in Kenya. *Agric Ecosyst Environ*.
561 2008;127: 31–36. doi:10.1016/j.agee.2008.02.002

- 562 36. Roulston TH, Goodell K. The Role of Resources and Risks in Regulating Wild Bee
563 Populations. *Annu Rev Entomol.* 2011;56: 293–312. doi:10.1146/annurev-ento-
564 120709-144802
- 565 37. Biesmeijer JC, Roberts SPM, Reemer M, Ohlemüller R, Edwards M, Peeters T, et
566 al. Parallel Declines in Pollinators and Insect-Pollinated Plants in Britain and the
567 Netherlands. *Science* (80-). 2006;313: 351–354. doi:10.1126/science.1127863
- 568 38. Robinson RA, Sutherland WJ. Post-war changes in arable farming and biodiversity
569 in Great Britain. *J Appl Ecol.* 2002;39: 157–176. doi:10.1046/j.1365-
570 2664.2002.00695.x
- 571 39. Westphal C, Bommarco R, Carré G, Lamborn E, Morison N, Petanidou T, et al.
572 MEASURING BEE DIVERSITY IN DIFFERENT EUROPEAN HABITATS
573 AND BIOGEOGRAPHICAL REGIONS. *Ecol Monogr.* 2008;78: 653–671.
574 doi:10.1890/07-1292.1
- 575 40. Morandin LA, Winston ML, Abbott VA, Franklin MT. Can pastureland increase
576 wild bee abundance in agriculturally intense areas? *Basic Appl Ecol.* 2007;8: 117–
577 124. doi:10.1016/j.baae.2006.06.003
- 578 41. Coll M. Conservation biological control and the management of biological control
579 services: are they the same? *Phytoparasitica.* 2009;37: 205–208.
580 doi:10.1007/s12600-009-0028-5
- 581 42. Goulson D, Darvill B. Niche overlap and diet breadth in bumblebees; are rare
582 species more specialized in their choice of flowers? *Apidologie.* 2004;35: 55–63.
583 doi:10.1051/apido:2003062
- 584 43. Minckley RL, Roulston TH, Williams NM. Resource assurance predicts specialist

- 585 and generalist bee activity in drought. *Proc R Soc B Biol Sci.* 2013;280: 20122703.
586 doi:10.1098/rspb.2012.2703
- 587 44. Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C. Landscape
588 perspectives on agricultural intensification and biodiversity - ecosystem service
589 management. *Ecol Lett.* 2005;8: 857–874. doi:10.1111/j.1461-0248.2005.00782.x
- 590 45. Vanbergen AJ, Initiative the IP. Threats to an ecosystem service: pressures on
591 pollinators. *Front Ecol Environ.* 2013;11: 251–259. doi:10.1890/120126
- 592 46. Ginsberg HS. Foraging Movements of *Halictus ligatus* (Hymenoptera: Halictidae)
593 and *Ceratina calcarata* (Hymenoptera: Anthophoridae) on *Chrysanthemum*
594 *leucanthemum* and *Erigeron annuus*. *J Kansas Entomol Soc.* 1985;58: 19–26.
- 595 47. Ginsberg HS. Foraging Ecology of Bees in an Old Field. *Ecology.* 1983;64: 165–
596 175. doi:10.2307/1937338
- 597 48. Goulson D, Lye GC, Darvill B. Decline and Conservation of Bumble Bees. *Annu*
598 *Rev Entomol.* 2008;53: 191–208. doi:10.1146/annurev.ento.53.103106.093454
- 599 49. Goulson D, Lepais O, O’Connor S, Osborne JL, Sanderson RA, Cussans J, et al.
600 Effects of land use at a landscape scale on bumblebee nest density and survival. *J*
601 *Appl Ecol.* 2010;47: 1207–1215. doi:10.1111/j.1365-2664.2010.01872.x
- 602 50. Power AG. Ecosystem services and agriculture: tradeoffs and synergies. *Philos*
603 *Trans R Soc B Biol Sci.* 2010;365: 2959–2971. doi:10.1098/rstb.2010.0143
- 604 51. Matson PA, Parton WJ, Poser AG, M J S. Agricultural Intensification and
605 Ecosystem Properties. *Science (80-).* 1997;277: 504–509.
606 doi:10.1126/science.277.5325.504
- 607 52. Roubik DW. Pollination of cultivated plants in the tropics. Roubik DW, editor.

- 608 Agricultural Services Bulletin. 1995. Available: <http://www.fao.org/3/a-v5040e.pdf>
- 609 53. Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang YUN, et al. The
610 Melting Himalayas : Cascading Effects of Climate Change on Water , Biodiversity
611 , and Livelihoods. *Conserv Biol.* 2009;23: 520–530. doi:10.1111/j.1523-
612 1739.2009.01237.x
- 613 54. Klein JA, Harte J, Zhao X-Q. Experimental warming causes large and rapid
614 species loss, dampened by simulated grazing, on the Tibetan Plateau. *Ecol Lett.*
615 2004;7: 1170–1179. doi:10.1111/j.1461-0248.2004.00677.x
- 616 55. Podani J, Schmera D. On dendrogram based measures of functional diversity.
617 *Oikos.* 2006;1: 179–185. doi:10.1111/j.2006.0030-1299.15048.x
- 618 56. Walker MD, Wahren CH, Hollister RD, Henry GHR, Ahlquist LE, Alatalo JM, et
619 al. From The Cover: Plant community responses to experimental warming across
620 the tundra biome. *Proc Natl Acad Sci.* 2006;103: 1342–1346.
621 doi:10.1073/pnas.0503198103
- 622 57. Saavedra F, Inouye DW, Price M V., Harte J. Changes in flowering and abundance
623 of *Delphinium nuttallianum* (Ranunculaceae) in response to a subalpine climate
624 warming experiment. *Glob Chang Biol.* 2003;9: 885–894. doi:10.1046/j.1365-
625 2486.2003.00635.x
- 626 58. Kudo G, Ida TY. Early onset of spring increases the phenological mismatch
627 between plants and pollinators. *Ecology.* 2013;94: 2311–2320. doi:10.1890/12-
628 2003.1
- 629 59. Williams JW, Jackson ST. Novel climates, no-analog communities, and ecological
630 surprises. *Front Ecol Environ.* 2007;5: 475–482. doi:10.1890/070037

- 631 60. Xu J, Badola R, Chettri N, Chaudhary RP, Zomer R, Pokhrel B, et al. Sustaining
632 Biodiversity and Ecosystem Services in the Hindu Kush Himalaya. Springer
633 International Publishing; 2019. doi:10.1007/978-3-319-92288-1
- 634 61. Global Pollination Project. Conservation & Management of Pollinators for
635 Sustainable Agriculture through an Ecosystem Approach. In: Food and Agriculture
636 Organization of the United Nations [Internet]. 2015 p. 1. Available:
637 [https://www.thegef.org/project/conservation-management-pollinators-sustainable-](https://www.thegef.org/project/conservation-management-pollinators-sustainable-agriculture-through-ecosystem-approach)
638 [agriculture-through-ecosystem-approach](https://www.thegef.org/project/conservation-management-pollinators-sustainable-agriculture-through-ecosystem-approach)
- 639 62. Partap U, Pratap T. Warning Signals from the Apple valleys of the Hindu Kush-
640 Himalayas: Productivity Concerns and Pollination Problems. Kathmandu, Nepal;
641 2002.
- 642 63. Pratap U, Pratap T. Managed Crop Pollination: The Missing Dimension of
643 Mountain Agricultural Productivity. Kathmandu, Nepal: International Centre for
644 Integrated Mountain Development; 1997.
- 645 64. Gurung MB, Partap U, Sharma HK, Islam N, Tamag NB. Beekeeping Training for
646 Farmers in the Himalayas - Resource Manual for Trainers. Kathmandu, Nepal:
647 International Centre for Integrated Mountain Development, Kathmandu; 2012.
- 648 65. Ahmad F, Joshi SR, Gurung MB. The Himalayan Cliff Bee *Apis laboriosa* and the
649 honey Hunters of Kaski - Indigenous Honeybees of the Himalayas (Vol 1).
650 Kathmandu, Nepal: International Centre for Integrated Mountain Development;
651 2003.
- 652 66. Verma L, Partap U. The Asian hive bee, *Apis cerana*, as a pollinator in vegetable
653 seed production. Kathmandu, Nepal: International Centre for Integrated Mountain
654 Development; 1993.

- 655 67. Pratap U. Honeybees and Ecosystem Services in the Himalayas. In: Spehn EM,
656 Rudmann-Maurer K, Körner C, Maselli D, editors. Mountain Biodiversity and
657 global change. Global Mountain Biodiversity Assessment (GMBA) of
658 DIVERSITAS, Institute of Botany, University of Basel with the support of the
659 Swiss Agency for Development and Cooperation (SDC); 2010.
660 doi:10.1016/j.cca.2007.05.017
- 661 68. Pratap U. Innovations in revival strategies for declining pollinators with particular
662 reference to the indigenous honey bees: experiences of ICIMOD's initiatives in the
663 Hindu Kush-Himalayan region. In: Verma AK, Bhardwaj SP, Gupta PR, editors.
664 Proceedings of the National Symposium "Perspectives and Challenges of
665 Integrated Pest Management for Sustainable Agriculture", Himachal Pradesh, India,
666 19-21, November 2010. Indian Society of Pest Management and Economic
667 Zoology; 2010. pp. 85–95.
- 668 69. Jiju JS, Kumar A, Uniyal VP. Preliminary Study on Diversity of Insect Pollinators
669 in Navdanya Organic Farm, Dheradun, Uttarakhand, India. Indian For. 2017;143:
670 1042–1045.
- 671 70. Agricultural Department. Agricultural Statistics Data. In: Agriculture Department
672 Govt. Of Uttarakhand [Internet]. 2019 p. 1. Available:
673 <http://agriculture.uk.gov.in/pages/show/221-agriculture-statistics-data>
- 674 71. Bhattacharjee P, Singhal RS, Kulkarni PR. Basmati rice: a review. Int J Food Sci
675 Technol. 2002;37: 1–12. doi:10.1046/j.1365-2621.2002.00541.x
- 676 72. Mahajan BVC, Dillon BS. Evaluation of different cultivars of litchi (*Litchi*
677 *chinensis*) under sub-montaneous regions of Punjab. Haryana J Horti Sci.
678 2000;29: 184 ref.2.

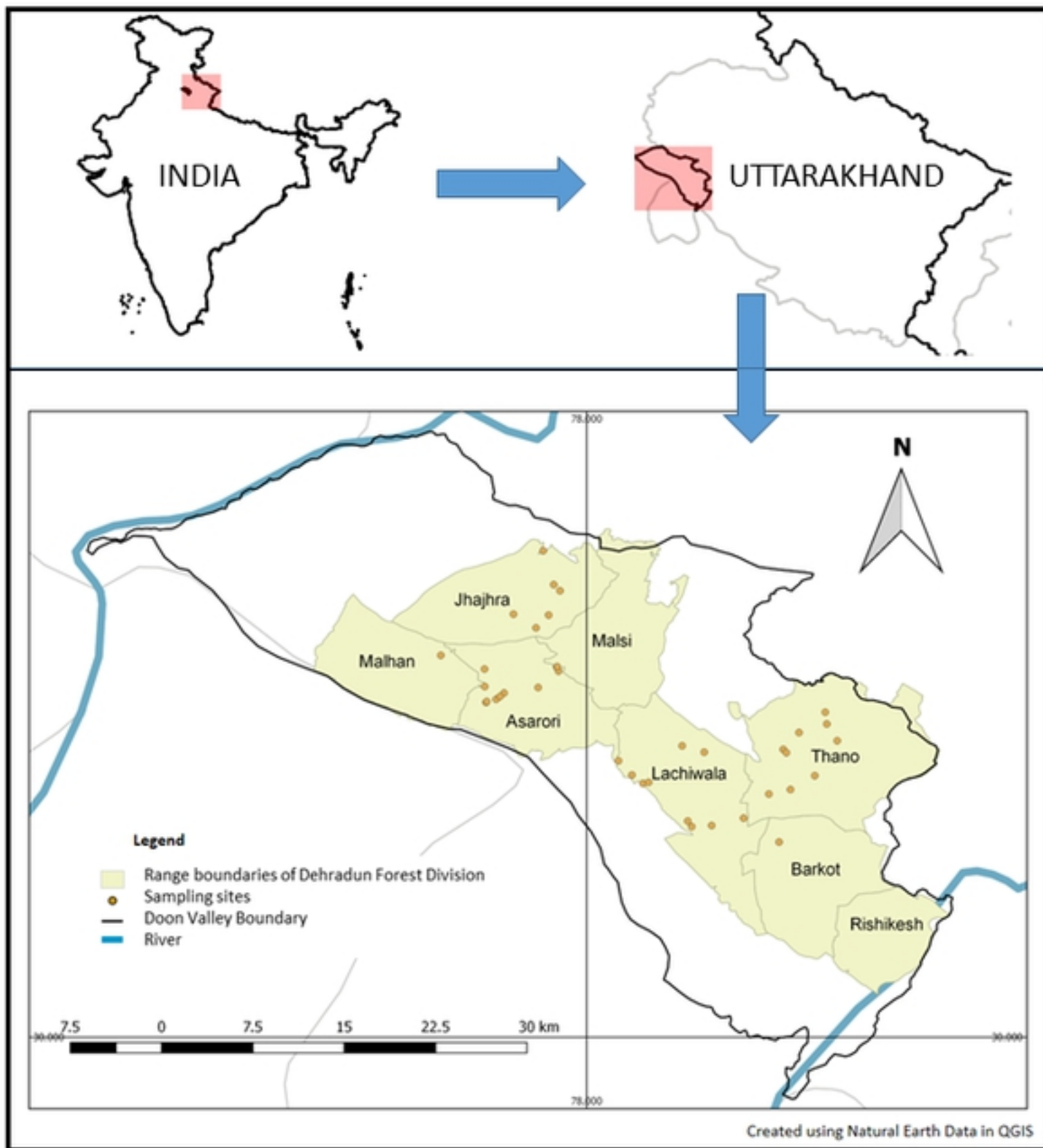
- 679 73. Pande PC, Vibhuti V, Awasthi P, Bargali K, Bargali SS. Agro-Biodiversity of
680 Kumaun Himalaya, India: A Review. *Curr Agric Res J.* 2016;4: 16–34.
681 doi:10.12944/CARJ.4.1.02
- 682 74. Lebuhn G, Droege S, Connor EF, Gemmill-Herren B, Potts SG, Minckley RL, et
683 al. Detecting insect pollinator declines on regional and global scales. *Conserv Biol.*
684 2013;27: 113–20. doi:10.1111/j.1523-1739.2012.01962.x
- 685 75. Lebuhn G, Griswold T, Minckley R, Droege S, Roulson T, Cane J, et al. A
686 standardized method for monitoring Bee Populations - The Bee inventory (BI)
687 Plot. 2003. p. 11. Available: <http://online.sfsu.edu/beeplot/pdfs/Bee Plot 2003.pdf>
- 688 76. Leong JM, Thorp RW. Colour-coded sampling: the pan trap colour preferences of
689 oligolectic and nonoligolectic bees associated with a vernal pool plant. *Ecol*
690 *Entomol.* 1999;24: 329–335. doi:10.1046/j.1365-2311.1999.00196.x
- 691 77. Toler TR, Evans EW, Tepedino VJ. Pan-trapping for bees (Hymenoptera :
692 Apiformes) in Utah’s West Desert: the importance of color diversity. *Pan-Pac*
693 *Entomol.* 2005;81: 103–113.
- 694 78. Barratt BIP, Derraik JGB, Rufaut CG, Goodman AJ, Dickinson KJM.
695 Morphospecies as a substitute for Coleoptera species identification, and the value
696 of experience in improving accuracy. *J R Soc New Zeal.* 2003;33: 583–590.
697 doi:10.1080/03014223.2003.9517746
- 698 79. Derraik JGB, Early JW, Closs GP, Dickinson KJM. Morphospecies and
699 Taxonomic Species Comparison for Hymenoptera. *J Insect Sci.* 2010;10: 1–7.
700 doi:10.1673/031.010.10801
- 701 80. Derraik JGB, Closs GP, Dickinson KJM, Sirvid P, Barratt BIP, Patrick BH.

- 702 Arthropod Morphospecies versus Taxonomic Species: a Case Study with Araneae,
703 Coleoptera, and Lepidoptera. *Conserv Biol.* 2002;16: 1015–1023.
704 doi:10.1046/j.1523-1739.2002.00358.x
- 705 81. Clarke KR, Warwick RM. Change in marine communities: an approach to
706 statistical analysis and interpretation. Plymouth; 2001.
- 707 82. Clarke K, Gorley R. PRIMER v5: User Manual/Tutorial. Plymouth, UK:
708 PRIMER-E; 2001. p. 91.
- 709 83. Chazdon RL, Chao A, Colwell RK, Lin S-Y, Norden N, Letcher SG, et al. A novel
710 statistical method for classifying habitat generalists and specialists. *Ecology.*
711 2011;92: 1332–1343. doi:10.1890/10-1345.1
- 712 84. Oksanen J. *Vegan: ecological diversity.* R Doc. 2016; 12.
713 doi:10.1029/2006JF000545
- 714 85. R Core Team. R: A language and environment for statistical computing. R
715 Foundation for Statistical Computing, Vienna, Austria. 2016. Available:
716 <https://www.r-project.org/>
- 717 86. Ascher JS, Pickering J. Discover Life bee species guide and world checklist
718 (Hymenoptera: Apoidea: Anthophila). In: Discover Life [Internet]. 2018.
719 Available: http://www.discoverlife.org/mp/20q?guide=Apoidea_species
- 720 87. Garimaldi D, Engel MS. *Evolution of the Insects.* New York: Cambridge
721 University Press; 2005.
- 722 88. Goulson D, Darvill B. Niche overlap and diet breadth in bumblebees; are rare
723 species more specialized in their choice of flowers? *Apidologie.* 2004;35: 55–63.
724 doi:10.1051/apido:2003062

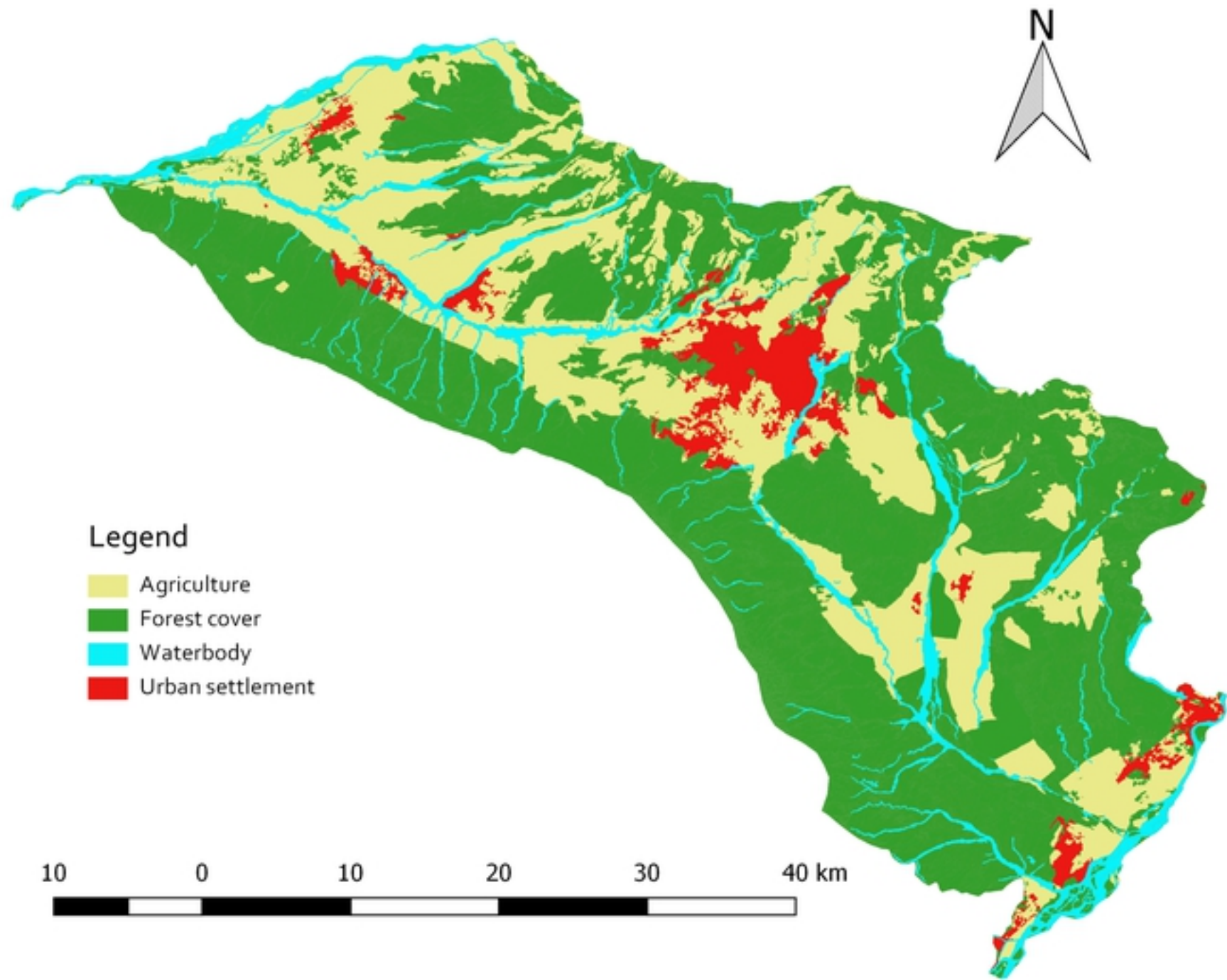
- 725 89. Williams NM, Minckley RL, Silveira FA. Variation in Native Bee Faunas and its
726 Implications for Detecting Community Changes. *Conserv Ecol.* 2001;5: art7.
727 doi:10.5751/ES-00259-050107
- 728 90. Sakagami SF, Fukuda H. Instructions for use Wild Bee Survey at the Campus of
729 Hokkaido Universityl). *Zoology.* 1973;19: 190–250.
- 730 91. Tepedino AVJ, Stanton NL. Nordic Society Oikos Diversity and Competition in
731 Bee-Plant Communities on Short-Grass Prairie Published by : Wiley on behalf of
732 Nordic Society Oikos Stable URL : <http://www.jstor.org/stable/3544376>
733 REFERENCES Linked references are available on JSTOR for. *Oikos.* 1981;36:
734 35–44.
- 735 92. Silveira FA, Rocha LB, Cure JR, Oliveira MJ. Abelhas silvestres (Hymenoptera,
736 Apoidea) da Zona da Mata de Minas Gerais. II. Diversidade, abundância e fontes
737 de alimento em uma pastagem abandonada em Ponte Nova. *Rev Bras Entomol.*
738 1993;37: 595–610.
- 739 93. Carvalho AMC, Bego LR. Studies on Apoidea fauna of cerrado vegetation at the
740 Panga Ecological Reserve, Uberlândia, MG, Brazil. *Rev Bras Entomol.* 1996;40:
741 147–156.
- 742 94. Timberlake PH, Michener CD. The bees of the genus *Proteriades*. *Univ Kansas Sci*
743 *Bull.* 1950;XXXIII: 387–430.
- 744 95. Michener CD, McGinley RJ, Danforth BN. The Bee Genera of North and Central
745 America (Hymenoptera: Apoidea). Smithsonian Institution Press. Washington,
746 DC.: Smithsonian Institution Press; 1994. Available:
747 <http://www.eupublishing.com/doi/abs/10.3366/anh.1995.22.1.141>

- 748 96. Mas AH, Dietsch T V. LINKING SHADE COFFEE CERTIFICATION TO
749 BIODIVERSITY CONSERVATION: BUTTERFLIES AND BIRDS IN
750 CHIAPAS, MEXICO. *Ecol Appl*. 2004;14: 642–654. doi:10.1890/02-5225
- 751 97. Ricketts TH, Regetz J, Steffan-Dewenter I, Cunningham SA, Kremen C,
752 Bogdanski A, et al. Landscape effects on crop pollination services: Are there
753 general patterns? *Ecol Lett*. 2008;11: 499–515. doi:10.1111/j.1461-
754 0248.2008.01157.x
- 755 98. Banks JE, Hannon LM, Dietsch T V., Chandler M. Effects of seasonality and farm
756 proximity to forest on Hymenoptera in Tarrazú coffee farms. *Int J Biodivers Sci*
757 *Ecosyst Serv Manag*. 2014;10: 128–132. doi:10.1080/21513732.2014.905494
- 758 99. Klein A-MM, Steffan-Dewenter I, Tschardt T. Fruit set of highland coffee
759 increases with the diversity of pollinating bees. *Proc Biol Sci*. 2003;270: 955–61.
760 doi:10.1098/rspb.2002.2306
- 761 100. Baños-Picón L, Torres F, Tormos J, Gayubo SF, Asís JD. Comparison of two
762 Mediterranean crop systems: Polycrop favours trap-nesting solitary bees over
763 monocrop. *Basic Appl Ecol*. 2013;14: 255–262. doi:10.1016/j.baae.2012.12.008
- 764 101. Maikhuri RK, Rao KS, Saxena KG. Traditional crop diversity for sustainable
765 development of Central Himalayan agroecosystems. *Int J Sustain Dev World Ecol*.
766 1996;3: 8–31. doi:10.1080/13504509609469926
- 767 102. Briggs HM, Perfecto I, Brosi BJ. The Role of the Agricultural Matrix: Coffee
768 Management and Euglossine Bee (Hymenoptera: Apidae: Euglossini)
769 Communities in Southern Mexico. *Environ Entomol*. 2013;42: 1210–1217.
770 doi:10.1603/EN13087

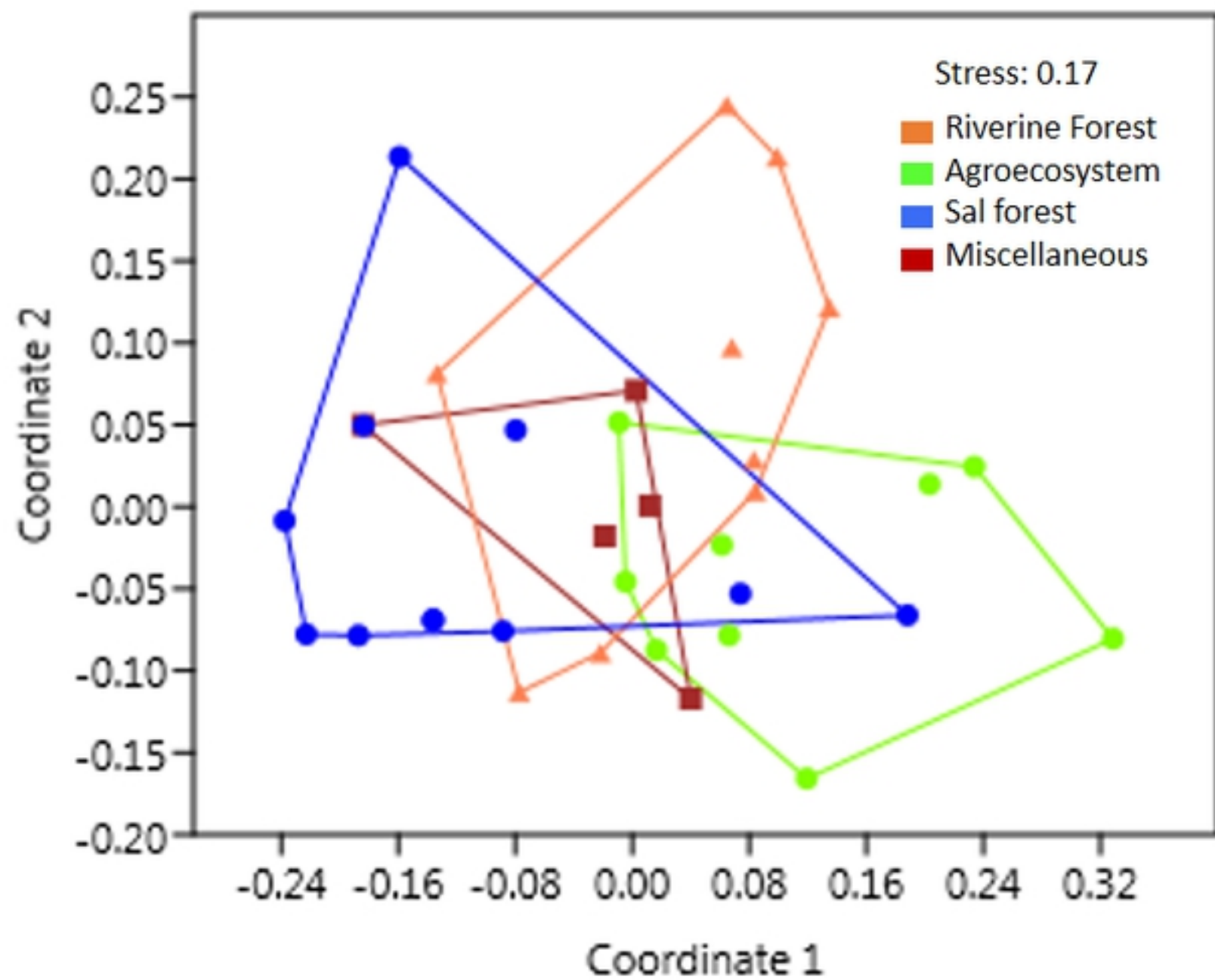
- 771 103. Morandin LA, Kremen C. Hedgerow restoration promotes pollinator populations
772 and exports native bees to adjacent fields. *Ecol Appl.* 2013;23: 829–839.
773 doi:10.1890/12-1051.1
- 774 104. Morandin LA, Kremen C. Bee Preference for Native versus Exotic Plants in
775 Restored Agricultural Hedgerows. *Restor Ecol.* 2013;21: 26–32.
776 doi:10.1111/j.1526-100X.2012.00876.x
- 777 105. Evenson RE, Golin D. Assessing the Impact of the Green Revolution, 1960 to
778 2000. *Science (80-)*. 2003;300: 758–762. doi:10.1126/science.1078710
- 779 106. Di Marco M, Ferrier S, Harwood TD, Hoskins AJ, Watson JEM. Wilderness areas
780 halve the extinction risk of terrestrial biodiversity. *Nature.* 2019.
781 doi:10.1038/s41586-019-1567-7
- 782 107. Baudron F, Giller KE. Agriculture and nature: Trouble and strife? *Biol Conserv.*
783 2014;170: 232–245. doi:10.1016/j.biocon.2013.12.009



Figure

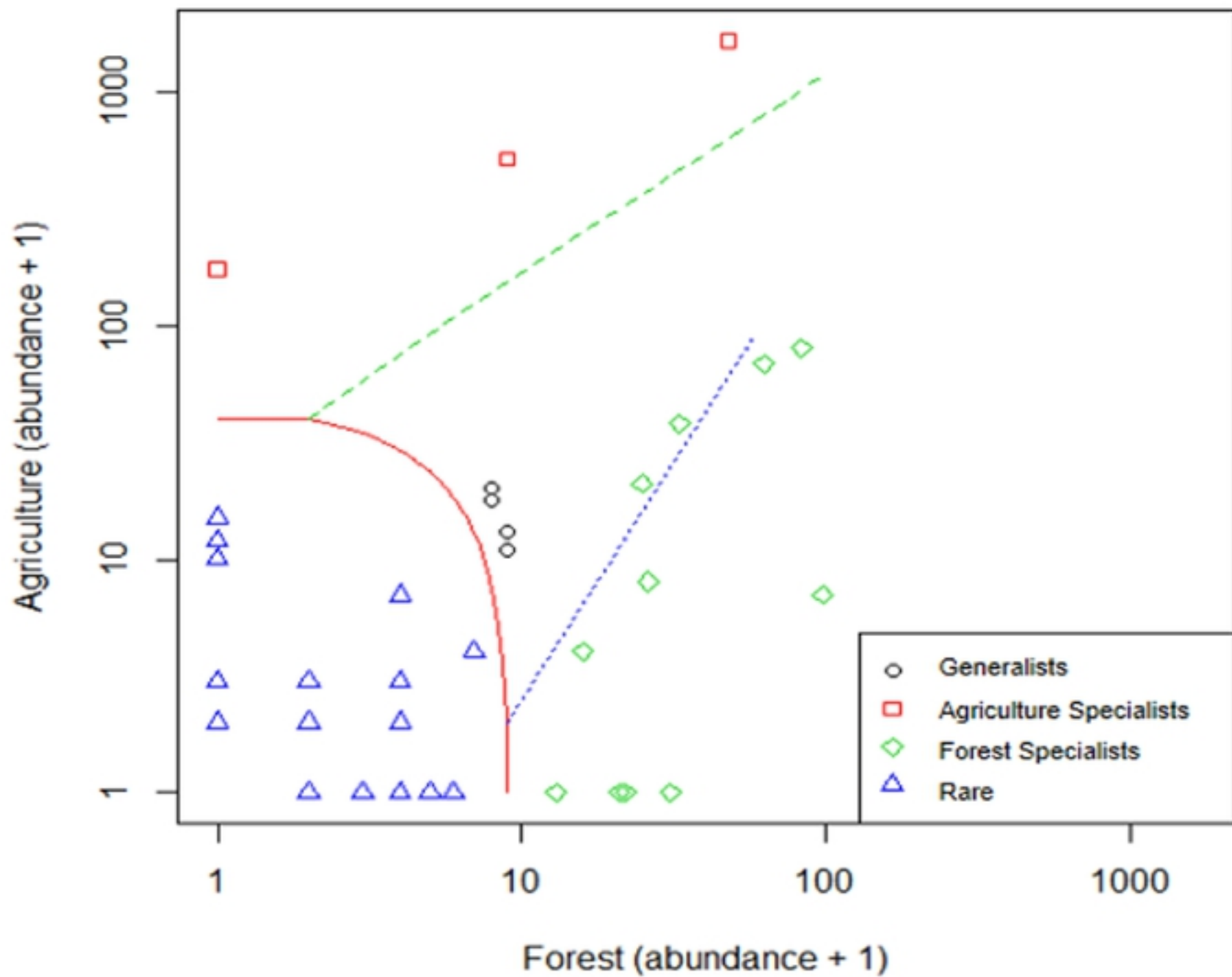


Figure

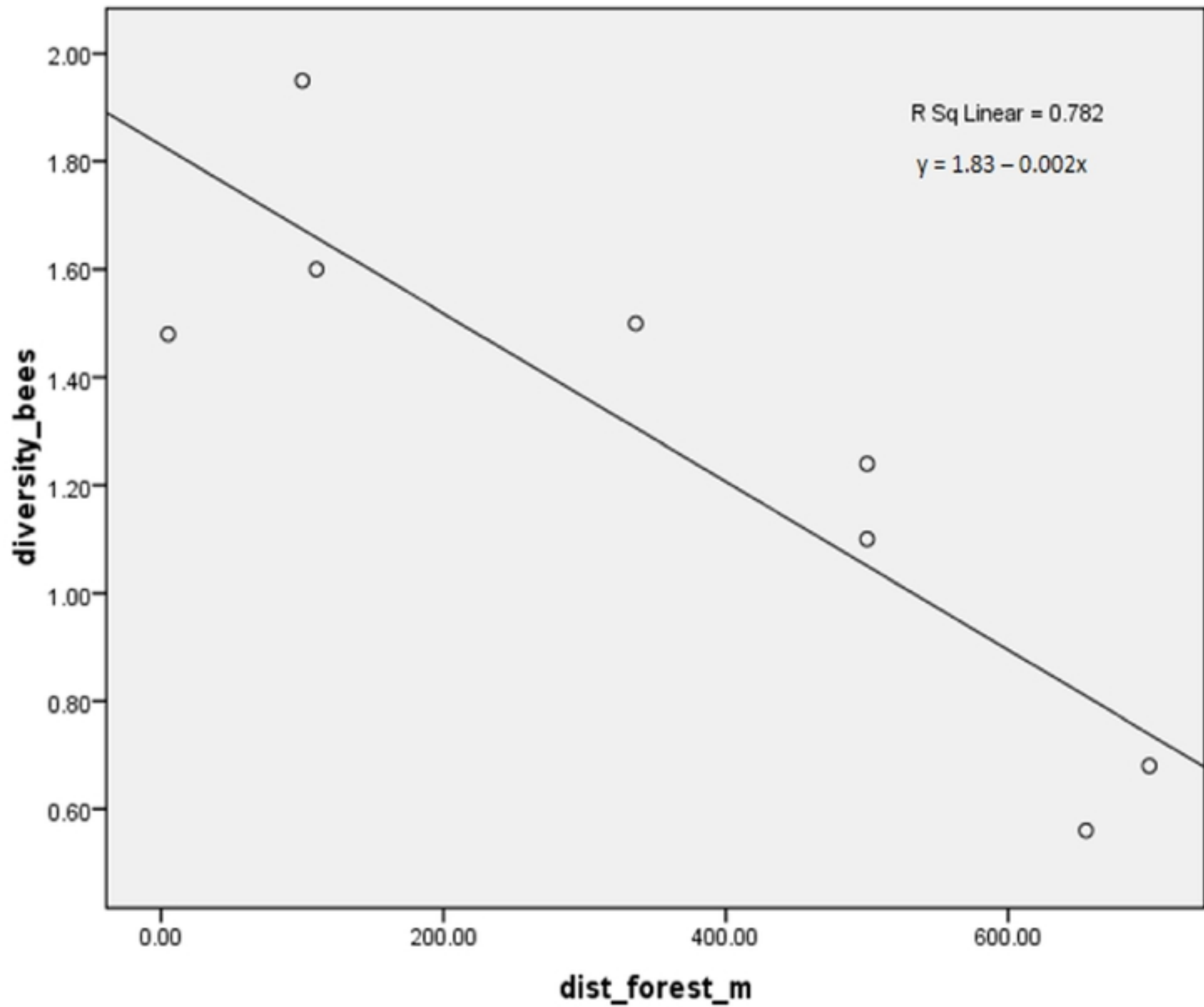


Figure

Species Classification



Figure



Figure