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Bee-plant interactions and network structure across land cover types in New Zealand

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Research Article

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Abstract

Land cover change and biological invasions alter pollinator communities and the distribution of floral resources, but how these changes influence specific bee–plant interactions across different landscapes often remains unclear. We reconstructed bee–plant interaction networks from New Zealand using 2,266 interactions extracted from digitised natural history collections and compared interaction patterns between native and exotic land cover types. Native bees accounted for most recorded interactions across all land cover types. Bee and plant biostatus showed strong non-random associations, with native bees interacting mainly with native plants and exotic bees interacting more frequently with exotic plants. Network-level specialisation was moderate to high and varied little among land cover types (H2' = 0.63–0.68), although species-level specialisation differed substantially among bee species. Preference indices showed that most native bee species exhibited neutral or negative preferences for exotic plants, whereas several exotic bee species preferentially visited exotic plants. Temporal analyses further showed that native bees increasingly incorporated exotic plants into their interactions through time, while exotic bees showed increased use of native plants. Our results suggest that changes to land cover influences bee–plant interaction patterns while native and exotic bees differ in their use of floral resources.

Introduction

Animal pollinators play an important role in the reproduction of most flowering plants and contribute substantially to global ecosystem and agriculture (Ackerman 2000; Ollerton et al. 2011; Potts et al. 2016). Pollinators are affected by habitat modification, biological invasions, climate change, and other anthropogenic pressures (Janousek et al. 2023; Walters 2016; Pedersen et al. 2025; Piché-Mongeon & Guzman-Novoa 2024), with both increases and declines reported for different pollinator groups across regions (Biesmeijer et al. 2006; Bartomeus et al. 2013; Scheper et al. 2014; Potts et al. 2010). However, changes in pollinator abundance or species richness do not fully describe how pollination systems respond to these disturbances. Pollination depends on interactions between plants and pollinators, and these interactions may change even when both interacting species remain present (Valiente-Banuet et al. 2015). These changes may precede detectable shifts in pollinator populations or community composition (Huang et al. 2021; Valiente-Banuet et al. 2015; Vizentin-Bugoni & Maruyama 2023).

Plant-pollinator interactions depend on the spatial and temporal co-occurrence of interacting species, as well as the matching of their morphological and behavioural traits (Vázquez et al. 2020). Pollinators differ in their degree of specialization, generalist species often adjust their foraging behaviour in response to changes in the composition, abundance, or phenology of floral resources, while specialist species rely on a narrower range of host plants (Gómez et al. 2025). Such flexibility may result in interaction rewiring, in which existing interactions are replaced by new ones (Trunschke et al. 2024; Brett et al. 2024; Noreika et al. 2019). By contrast, highly specialised interactions are less likely to be replaced following environmental disturbance because suitable alternative partners are often lacking (Vizentin-Bugoni & Maruyama 2023).

Land cover change is one of the main drivers of change in pollination systems (Dicks et al. 2021). The conversion of native vegetation to agricultural, plantation, and urban landscapes changes the diversity, abundance, and spatial distribution of floral resources, as well as pollinator communities and habitat

connectivity (Balogh et al. 2025; Montti et al. 2017; Hung et al. 2017; Hobbs & Huenneke 1992). These changes can alter pollinator foraging behaviour and reshape the pollination networks. Biological invasion makes these changes even more complex. Exotic plants may provide new floral resources for native pollinators and compete with native plants, while exotic pollinators may form new interactions with native plants and compete with native pollinators for resources (Beggs & Wardle 2006; Stout & Morales 2009). However, not all pollinators respond to environmental change in the same way. Native and exotic bees differ in their evolutionary histories, ecological traits, and patterns of resource use. These differences may influence how they use floral resources and interact with plants under changing landscape.

The native bee species in New Zealand are relatively few but highly endemic (Donovan 2007). Exotic flowering plants and several exotic bee species are also widely established across a range of landscapes (Donovan 2007; Howlett et al. 2025). Although a few highly specialised pollination systems have been reported (Milliken et al. 2024), plant-pollinator interactions in New Zealand are generally considered to be relatively generalized (Donovan 2007). This has been linked to the prevalence of small, open, and pale-coloured flowers that are accessible to a wide range of insect visitors (Godley 1979). In addition, New Zealand has a high proportion of endemic plant species and has experienced huge land cover change over a relatively short period (Ewers et al. 2006). Together, these characteristics provide the ecological context for examining interactions between native and exotic species.

Understanding the pollination network across different land cover types requires data collected from a wide range of habitats. Field surveys are often limited to a small number of sites and sampling periods, making it difficult to compare interaction patterns across large spatial scales. However, natural history collections provide an alternative source of data (Bartomeus et al. 2013; Bartomeus et al. 2019). Specimen labels that include locality, date, habitat, and associated plant information, allow plant-insect interactions and networks to be reconstructed. The ongoing digitisation of museum collections has greatly improved access to these records and made it possible to examine interaction patterns across broad geographic areas and multiple land cover types (Bartomeus et al. 2013; Bartomeus et al. 2019).

In this study, we reconstructed bee-plant interaction networks from New Zealand using information from digitised natural history collections. We compared interaction patterns across different land cover types and examined differences in the use of native and exotic plants by native and exotic bees. We also explored temporal changes in plant use through time.

Methods and Materials

Data source

Information from GBIF was downloaded in Darwin Core standard format on 6 May 2025 (https://doi.org/10.15468/dl.q98yf3). The search was performed using the occurrence search interface with filters set to include only: i) “preserved specimens”, ii) occurrence status marked as “present” in New Zealand, and iii) searches restricted to four bee families in New Zealand: Apidae, Colletidae, Halictidae, and Megachilidae.

Data validation: bees

Using Donovan (2007), the taxonomic names of bee species were checked to ensure each was a valid name and not a synonym, and the biostatus of each species was obtained from Donovan (2007). Bee records include 40 species in nine genera in four families (Table 1). This was strongly dominated by Colletidae, which has five genera and 58% of all records (1,314 records), followed by Halictidae (1 genus, 22%, 503 records), Apidae (2 genera, 19%, 437 records) and Megachilidae (1 genus, < 1%, 12 records). Species-level sampling was similarly uneven, the five most frequently recorded species were *Bombus terrestris* (332 records), *Lasioglossum sordidum* (294), *Leioproctus pango* (204), *Leioproctus boltoni* (155) and *Leioproctus huakiwi* (146), together representing around half of all records, and the ten most common species accounted for over 70% of records (Supplementary Information 1).

Table 1
Number of occurrence records per bee species from GBIF dataset, with biostatus, specialisation (d') and preference (PI_exotic) metrics.

Genus and species	Biostatus	Records	Family	d'	PI_exotic
Bombus terrestris	Exotic	332	Apidae	0.839	0.710
Lasioglossum sordidum	Native	294	Halictiedae	0.542	-0.448
Leioproctus pango	Native	204	Colletidae	0.711	-0.364
Leioproctus boltoni	Native	155	Colletidae	0.477	-0.303
Leioproctus huakiwi	Native	146	Colletidae	0.537	0.232
Leioproctus imitatus	Native	134	Colletidae	0.681	-0.688
Lasioglossum mataroa	Native	102	Halictidae	0.871	0.704
Lasioglossum maunga	Native	90	Halictidae	0.620	-0.924
Nesocolletes paahaumaa	Native	85	Colletidae	0.518	0.546
Hylaeus capitosus	Native	80	Colletidae	0.456	-0.289
Bombus ruderatus	Exotic	70	Apidae	0.549	0.776
Nesocolletes fulvescens	Native	70	Colletidae	0.693	0.462
Nesocolletes monticola	Native	59	Colletidae	0.470	0.821
Hylaeus agilis	Native	56	Colletidae	0.484	-0.728
Leioproctus vestitus	Native	53	Colletidae	0.577	-0.553
Nesocolletes maritimus	Native	46	Colletidae	NA	NA
Hylaeus relegatus	Native	43	Colletidae	0.545	-0.709
Leioproctus waipounamu	Native	39	Colletidae	0.864	-1.000
Leioproctus metallicus	Native	26	Colletidae	0.693	-0.930
Leioproctus keehua	Native	25	Colletidae	0.859	-0.460
Bombus hortorum	Exotic	17	Apidae	0.425	0.821
Lasioglossum cognatum	Exotic	17	Halictidae	0.546	0.422
Leioproctus kanapuu	Native	14	Colletidae	0.392	-0.610
Hyleoides concinna	Exotic	13	Colletidae	1.000	0.821

Table 1
continued. Number of occurrence records per bee species from GBIF dataset, with biostatus, specialisation (d') and preference (PI_exotic) metrics.

Genus and species	Biostatus	Records	Family	d'	PI_exotic
Anthidium manicatum	Exotic	12	Halictidae	1.000	0.821
Leioproctus purpureus	Native	12	Colletidae	0.564	-1.000
Nesocolletes pekanui	Native	11	Colletidae	NA	NA
Hylaeus asperithorax	Exotic	10	Colletidae	0.720	-0.860
Leioproctus hukarere	Native	9	Colletidae	1.000	-1.000
Apis mellifera	Exotic	8	Apidae	0.646	-0.220
Hylaeus perhumilis	Exotic	8	Colletidae	0.971	0.821
Bombus subterraneus	Exotic	6	Apidae	0.597	0.821
Bombus spp.	Exotic	4	Apidae	NA	NA
Nesocolletes nunui	Native	4	Colletidae	NA	NA
Euryglossina	Exotic	3	Colletidae	NA	NA
Hylaeus kermadecensis	Native	3	Colletidae	1.000	-1.000
Hylaeus matamoko	Native	3	Colletidae	0.674	-1.000
Nesocolletes hudsoni	Native	2	Colletidae	0.105	-1.000

Data validation: plants

To obtain the correct taxonomic names of plant species, names were first obtained from the digitised records within the GBIF records from the categories of "habitat", "substrate", and "occurrenceRemarks", often because common names are used on labels (Supplementary Information 2). Plant names were unified by searching the New Zealand Plant Conversation Network (NZPCN) and the GBIF 'Species matching' tool, where the common name and the former scientific name were standardized to the current valid scientific name. The biostatus of the plant (native or exotic) was obtained through the NZPCN.

A total of 69 plant families were included in the GBIF dataset (Supplementary Information 3, 4). Records were uneven across families, with several groups contributing disproportionately to the dataset. The most frequently represented families were Myrtaceae (372 records), Asteraceae (294), Plantaginaceae (246), Actinidiaceae (216), Ericaceae (190), Fabaceae (168), Nothofagaceae (147), and Cupressaceae (112), while most remaining families appeared only rarely (< 10 records). Overall, plant biostatus was balanced, with native plants accounting for 51.4% of records (n = 1164) and exotic plants 48.6% (n = 1102).

Data: Land cover

The specimen labels of bees contain location information where geographic coordinates can be obtained. Lookup lists of NZAC sampling locations, and their coordinates were used to extract the corresponding land cover types at the time of sampling via the Land cover Database (LCDB) within the Land Resource Information System (LRIS) Portal (https://lris.scinfo.org.nz/). The different land cover classes were classified into a simple system of being either native or exotic. Three datasets were created, i) including all land cover types; ii) only native land cover; iii) only exotic land cover.

A total of 27 land cover classes were included in the dataset, ranging from native forests to agricultural and urban environments. Native land cover types (and the number of records): Alpine Grass/Herbfield (109); Broadleaved Indigenous Hardwoods (73); Gravel or Rock (12); Herbaceous Freshwater Vegetation (2); Indigenous Forest (45); Lake or Pond (16); Landslide (75); Mangrove (2); Manuka and/or Kanuka (21); Matagouri or Grey Scrub (8); River (11); Sand or Gravel (12); Sub Alpine Shrubland (12); Tall Tussock Grassland (28). Exotic land cover types (and the number of records): Built-up Area (settlement) (558); Deciduous Hardwoods (3); Depleted Grassland (11); Exotic Forest (37); Gorse and/or Broom (16); High Producing (Grassland (398); Low Producing Grassland (39); Mixed Exotic Shrubland (4); Orchard, Vineyard/Other Perennial Crop (1); Short-rotation Cropland (18); Transport Infrastructure (6); Urban Parkland/Open Space (61). No records were obtained from land cover classes: Estuarine open water, fernland, flaxland, herbaceous saline vegetation, and snow and ice. Land cover categories were highly skewed toward modified habitats: exotic (human-modified) land cover types (n = 1154, 73.8%) and native land cover types (n = 410, 26.2%).

Statistical Analysis

Chi-square tests were used to analyze the differences in the four possible associations between native and exotic bees and plants (i.e. native bee-native plant; native bee-exotic plant; exotic bee-native plant; exotic bee- exotic plant) for each land cover type.

Network-level specialisation was quantified using the standardized specialisation index H2' (Blüthgen et al. 2006). Bipartite interaction matrices were constructed for three datasets: (i) all land cover types combined, (ii) native land cover only, and (iii) exotic land cover only. Interaction weights were based on observed visitation frequencies between bee and plant species. The more selective a species, the larger is H2' for the web.

Species-level specialisation was quantified using the d' index for each bee species. The d' metric measures the deviation of observed interaction frequencies from those expected under random partner use, accounting for partner availability (Blüthgen et al. 2006). Values range from 0 (generalized interaction patterns) to 1 (high specialisation). Both H2' and d' were calculated using the R package *bipartite*.

To quantify species-level preferences for exotic versus native plants, a preference index (PI) was calculated for each bee species (Xie et al. 2008). For each species, observed visitation frequencies to native and exotic plants were compared with expected frequencies based on their proportional availability across the entire dataset. Expected visitation frequencies were calculated as the total number of interactions for each species multiplied by the overall proportion of native or exotic plant records in the dataset. Positive values indicate a ‘preference’ for exotic plants relative to expected interactions, negative values are the opposite.

To assess temporal changes in bee–plant interaction patterns, binomial generalized linear models (GLMs) were fitted separately for native and exotic bee groups. Plant biostatus was coded as a binary response variable (native plants = 0, exotic plants = 1), and year was included as the predictor variable. All models were fitted in R using the *stats* package.

Results

A total of 13,800 occurrence records were downloaded from GBIF, with records widely distributed across New Zealand (Supplementary Information 5). From this dataset, 22% of records had an interaction with a plant (n = 3,088 records), and of these, 73% (2,266 records) contained a georeference, which enabled land cover type to be obtained.

Across all land cover types, interactions were strongly structured by the native or exotic status of both bees and plants (Fig. 1). With all land cover types, native bees most frequently visited native plants (1,323 records), whereas exotic bees were predominantly associated with exotic plants (850 records). Interactions involving exotic bee and native plants were comparatively rare. This pattern changed when analyzing land cover separately. In exotic land cover, exotic bee-exotic plnat interactions were more common (387 records, 54.8%), while native bees showed increased visitation to exotic plants (319 records, 45.2%). Conversely, in native land cover, native-native interactions dominated (246 records, 78.6%), and exotic bees contributed relatively few visits overall (only 67 records total, 21.4%).

Chi-square tests showed strong non-random associations between bee and plant biostatus across all three datasets: all land covers ($\chi^2 = 743.77$, $p < 0.001$; Fig. 2); on native land covers ($\chi^2 = 62.14$, $p < 0.001$; Fig. 3); and on exotic land covers ($\chi^2 = 281.05$, $p < 0.001$; Fig. 4). In general, the bipartite networks for different land covers (Figs. 2, 3, 4) show that native bees are more diverse across all habitats, although both native and exotic bees have a great number of interactions. Native land covers are structured mainly around native plants, and native bees tend to visit native plants; while exotic land covers include a higher proportion of exotic plant interactions, and exotic bees interact only with exotic plants.

Network-level specialisation was moderate to high across all land cover types. The combined network exhibited an H2' value of 0.663. When analyzed separately, exotic land cover showed a slightly higher level of specialisation (H2' = 0.680) than native land cover (H2' = 0.628). Differences in H2' among land cover types were small, indicating broadly similar levels of overall network specialisation.

Species-level specialisation (d') varied widely among bee species (Fig. 5). Although native and exotic bees showed substantial overlap in d' values, exotic bees tended to exhibit slightly higher median specialisation, whereas native bees showed a more concentrated distribution of intermediate d' values.

Preference indices further revealed heterogeneity in species-level foraging behaviour. Most native bee species exhibited neutral to negative PI_exotic values, indicating lower proportional use, or avoidance, of exotic plants, whereas several exotic bee species showed strong positive PI_exotic values, reflecting disproportionate visitation to exotic plants (Fig. 6). Species with high interaction frequencies tended to show

more moderate preference values, whereas extreme PI values were often associated with lower sample sizes.

Generalised linear models (GLM) showed clear temporal shifts in the probability of native and exotic bees visiting native or exotic plants (Fig. 7). In all cases, year had a highly significant effect ($p < 0.001$), indicating temporal shifts in plant use. For native bees, the probability of visiting native plants declined significantly over time (coefficient = -0.024, $p < 0.001$), whereas visits to exotic plants increased significantly. For exotic bees, the probability of visiting native plants increased strongly through time (coefficient = 0.046, $p < 0.001$), while visits to exotic plants decreased accordingly.

Discussion

Effects of land cover change on pollination networks

This study demonstrates that the surrounding environment (i.e. land cover) influences recorded bee-plant associations and the distribution of interactions within the network. Land cover dominated by native plants showed primarily interactions between native bees and native plants, with relatively limited participation from exotic bees. In contrast, land cover dominated by exotic plants, interactions between native and exotic bees and exotic plants increased.

International studies have generally shown that land cover change often leads to simplification or even decline in pollination networks, with strong coupling between species of different biostatus (Parra-Tabla & Arceo-Gómez 2021; Pei et al. 2023; Valdovinos et al. 2018), although there are examples indicating that species-level network parameters are not significantly different between native and exotic species in certain ecological environments (Parra-Tabla et al. 2019). The New Zealand model is consistent with most international studies, suggesting that land use and land cover change can reconstruct plant-pollinator networks by altering the availability of flower resources, plant community composition, and the opportunity structure of interactions, often without uniformly affecting all pollinator populations.

Importantly, the observed differences in land cover types reflect changes in the context of interactions, rather than uniform responses among species. Land cover change altered the context in which interactions occur, and different bee populations responded differently to these changes. Therefore, network differences between land cover types redistributes interactions caused by changes in resource context rather than directly changing pollination function.

Native and exotic bees: flexibility or constraint?

A key finding of this study is the significant asymmetry in the use of native and exotic plants by native and exotic bees across land cover types. Native bees accounted for most recorded interactions and made extensive use of both native and exotic plants. In contrast, exotic bee interactions were fewer and clearly biased towards exotic plants, with very limited records of native plant use regardless of land cover type.

In land cover dominated by exotic plants, the interaction between native bees and exotic plants increased significantly, almost matching interactions between native bees and native plants. This pattern suggests a

high degree of flexibility in resource utilization by native bees, even when these resources are predominantly exotic plants (see recent review by Howlett et al 2025). Similar patterns have been observed in other areas (Parra-Tabla et al. 2019), where native pollinators incorporate exotic plants into their foraging resources in response to changes in the resource landscape. However, this apparent flexibility should is not necessarily evidence of preference or adaptive benefits. The increased use of exotic plants by native bees may also reflect a reduction in native plant resources in exotic-dominated environments, which effectively limits foraging choices. Meanwhile, exotic plants may not provide pollen of the same quality as native plants. In this context, interaction with exotic plants may represent a necessity rather than a choice, a distinction that cannot be resolved by natural history records.

Unlike native bees, exotic bees consistently exhibited lower levels of interaction with native plants across all land cover types, including native-dominant landscapes. This suggests more constrained or selective resource use patterns, possibly driven by preferences for familiar floral characteristics, higher rewards, or the abundance of exotic plants in human-modified environments. The commercial use of exotic bees for specific pollination services in human-modified environments may explain some patterns observed, but in this study the number of records occurring in orchards and croplands is very few (n = 19); the most common land cover types were exotic grasslands and urban areas. This shows the data was not heavily biased towards the use of some exotic bee species for pollination services in exotic land cover types. Differences in habitat use, phenology, or detection capabilities may also contribute to these patterns. Regardless of the underlying mechanisms, the persistence of this asymmetry across land cover types suggests that exotic bees are less flexible in plant use than native bees in the studied systems.

These results demonstrate that land cover change does not affect all pollinators equally. Instead, it reveals fundamental differences in the interactions between native and exotic bees with native and exotic plants. In New Zealand, native bees appear to be flexible generalists, able to adapt their resource use to changing landscapes, while exotic bees, even with native plant resources, remain closely associated with exotic plants (Howlett et al 2025). The extent to which this pattern applies beyond New Zealand remains uncertain. Unlike many continental floras, New Zealand has often been described as a relatively generalized pollination system, with many native plants bearing small, open flowers that are accessible to a wide range of insect visitors (Godley 1979). Such floral characteristics may reduce morphological barriers between native and exotic bees and plants, potentially influencing patterns of resource use observed in this study. Whether similar differences between native and exotic bees occur in more specialised pollination systems requires further investigation.

Temporal analyses showed that native bees increasingly incorporated exotic plants into their recorded interactions through time, accompanied by a corresponding decline in interactions with native plants. However, increased use of exotic plants should not be interpreted as evidence of preference, as changes in floral resource availability may also increase the likelihood of interactions with exotic species. Similar to the patterns observed across different land cover types, these temporal changes are therefore likely to reflect shifts in the availability and composition of floral resources rather than changes in the intrinsic preferences of native bees. Besides, exotic bees also showed an increase in interactions with native plants over time.

Further to the overall patterns, there were also marked differences in the specialisation and plant preferences of individual bee species. Several species exhibited extremely high specialisation (d' = 1.00), including *A. manicatum*, *H. concinna*, *H. kermadecensis*, and *L. hukarere*, indicating highly restricted interaction patterns. Relatively high levels of specialisation were also observed in *B. terrestris*, *L. mataroa*, *L. keehua*, *L. waipounamu*, and *H. perhumilis* (d' > 0.80). In contrast, *N. hudsoni* showed low specialisation (d' = 0.11), suggesting more generalised resource use. *Nesocolletes fulvescens* (d' = 0.69) and *L. pango* (d' = 0.71) also exhibited relatively high specialisation, consistent with Lim et al. (2025) and Milliken et al. (2024), who reported that these species had specialised pollination capabilities. Beyond variation in specialisation, preference patterns also differed markedly among species. Interestingly, three of the five native bee species that preferred exotic plants belonged to the endemic genus *Nesocolletes* (Fig. 6), highlighting considerable ecological variation even among closely related species.

Strengths and limitations of records-based networks

Record-based interaction networks provide a powerful tool for studying broad patterns of bee-plant associations across different landscapes (Bartomeus et al. 2013; Bartomeus et al. 2019). By integrating specimen and historical observation records, this approach captures extensive species interactions across time and space, enabling comparisons of native and exotic species across land cover types which are difficult to achieve in short-term field studies.

However, two main limitations must be considered when interpreting these results. First, record-based data are inherently subject to sampling bias. Field sampling efforts are uneven across different land cover types, locations, and time periods (Ward 2012), and may be influenced by accessibility, collector preferences, or the conspicuousness of certain species and plants, potentially leading to misidentification of pollinators and plants. These biases may exaggerate the apparent importance of common species and interactions while underestimating rarer or harder-to-detect species. Second, the presence of a bee-plant record does not necessarily mean effective pollination. Records may reflect brief encounters, nectar skimming, or incidental use, rather than successful pollen transfer, and may not record information such as visit frequency, duration, pollen load, or seed set.

Therefore, the networks analyzed here represent recorded associations rather than quantitative measurements of pollination intensity or reproductive contribution. To gain a better understanding of bee pollination in New Zealand, further work should focus on linking the results of historical data with field experiments and studies on species biology. For example, diet analyses and floral availability surveys could determine whether species-level specialisation observed in network data reflects true dietary restriction or differences in resource availability (Lim et al. 2025). In addition, direct measurements of pollen deposition or single-visit pollination effectiveness would further clarify whether frequent interactions translate into effective pollen transfer and reproductive success (Stavert et al. 2017). Therefore, network metrics based on historical records should be interpreted comparatively rather than absolutely.

Conclusion

Overall, our results show that land cover type influences bee–plant interaction patterns and that native and exotic bees differ in their use of native and exotic plants. Native bees exhibited greater flexibility in incorporating exotic plants into their recorded interactions, whereas exotic bees remained more strongly associated with exotic plants across different land cover types. These patterns suggest that changes in land cover and floral resources are associated with shifts in bee–plant interaction networks, although the functional consequences of these changes remain uncertain.

Declarations

Funding Declaration

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Author Contribution

H.Z. designed the work, prepared data, undertook statistical analyses, and prepared figures. D.W. designed and supervised the work. Both authors wrote and reviewed the manuscript."

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Data Availability

Publicly available in a repository: https://doi.org/10.15468/dl.q98yf3

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Figures

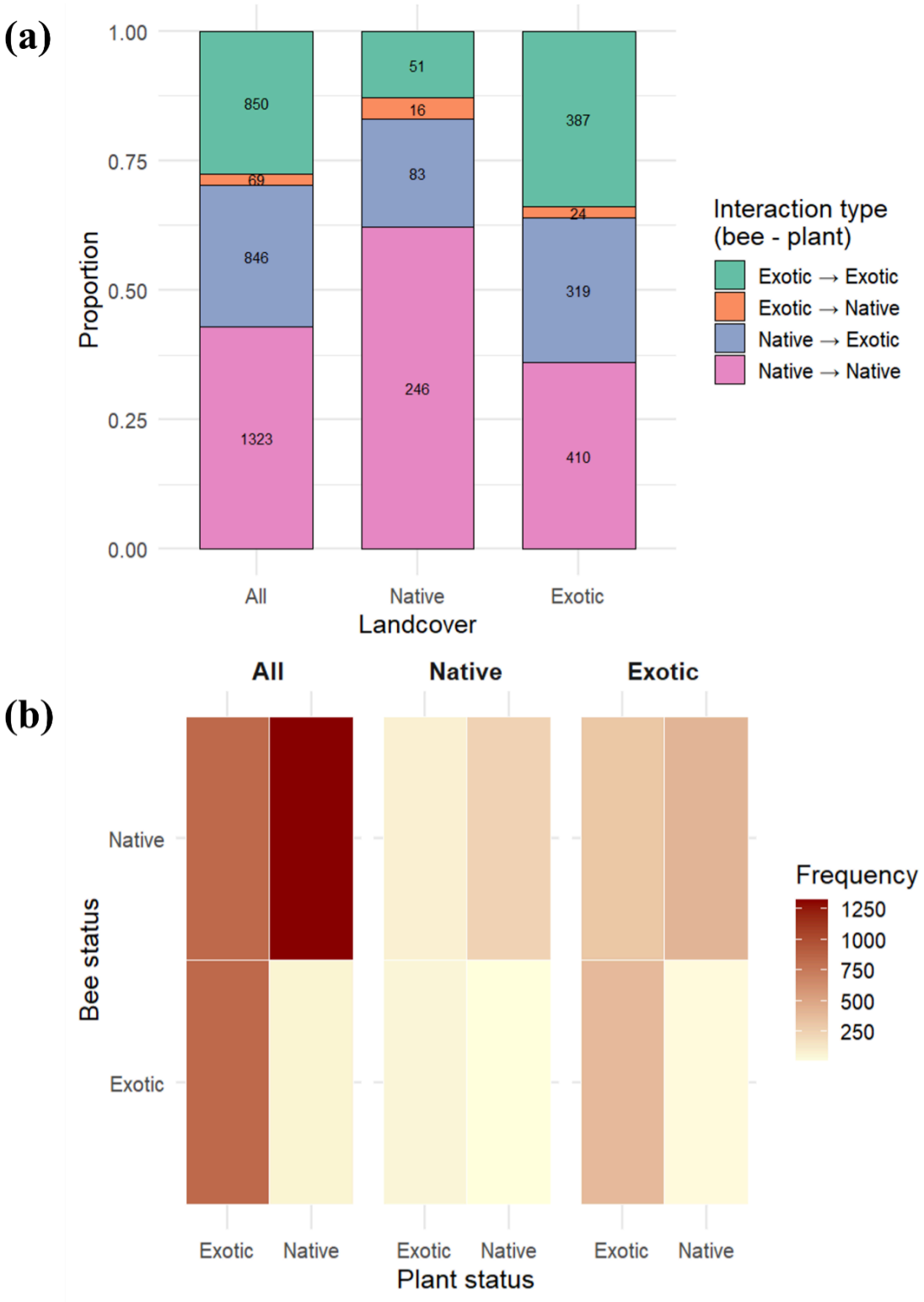


Figure 1

(a) Proportional contribution and (b) heatmap of the four bee–plant interaction types across three land cover categories.

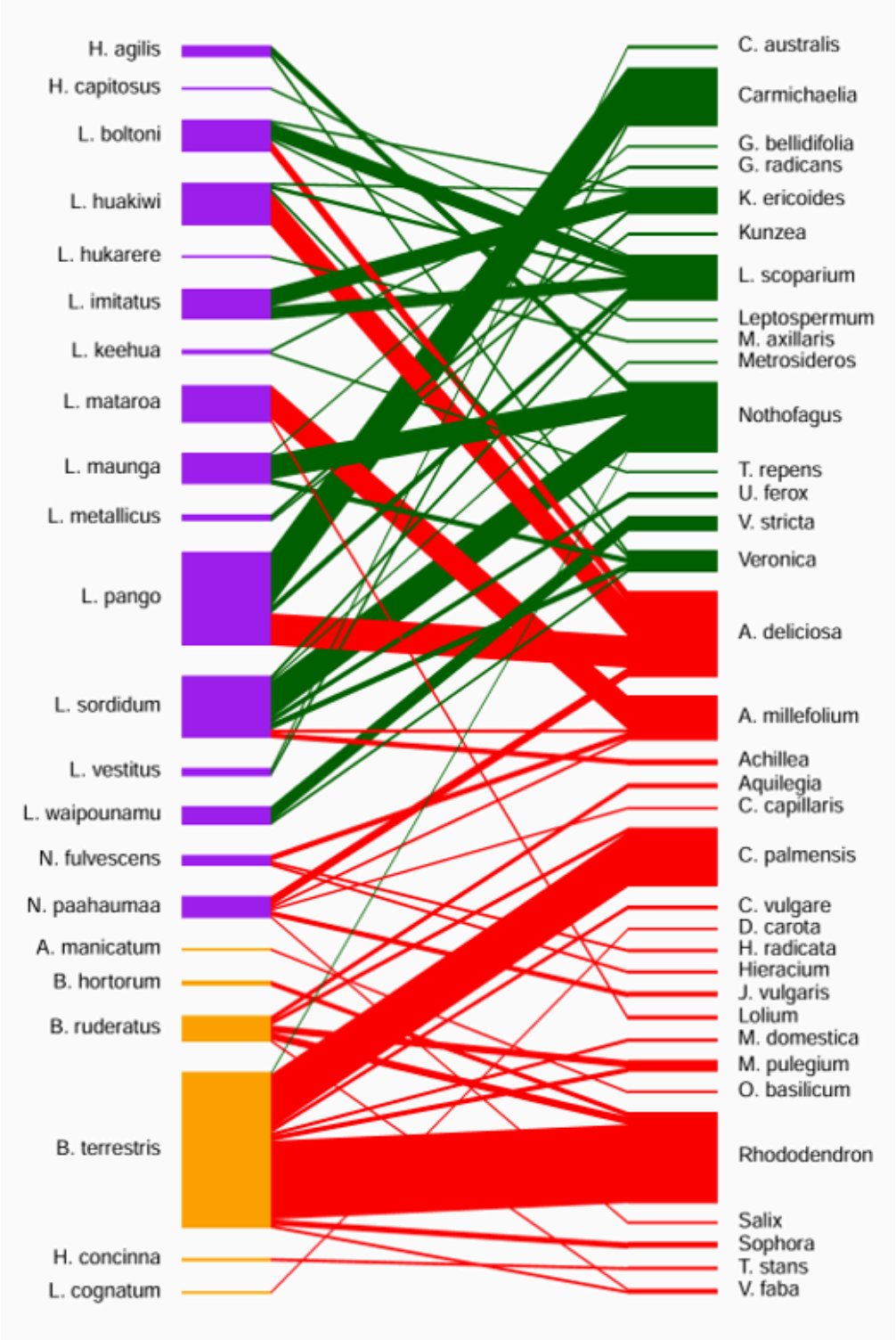


Figure 2

Bee-plant bipartite networks across all land cover classes. Bar widths represent interaction frequency. Colours indicate biostatus: purple - native bees; orange - exotic bees; green - native plants; red – exotic plants.



Figure 3

Bee-plant bipartite networks across native land cover types. Colours as for Figure 2.

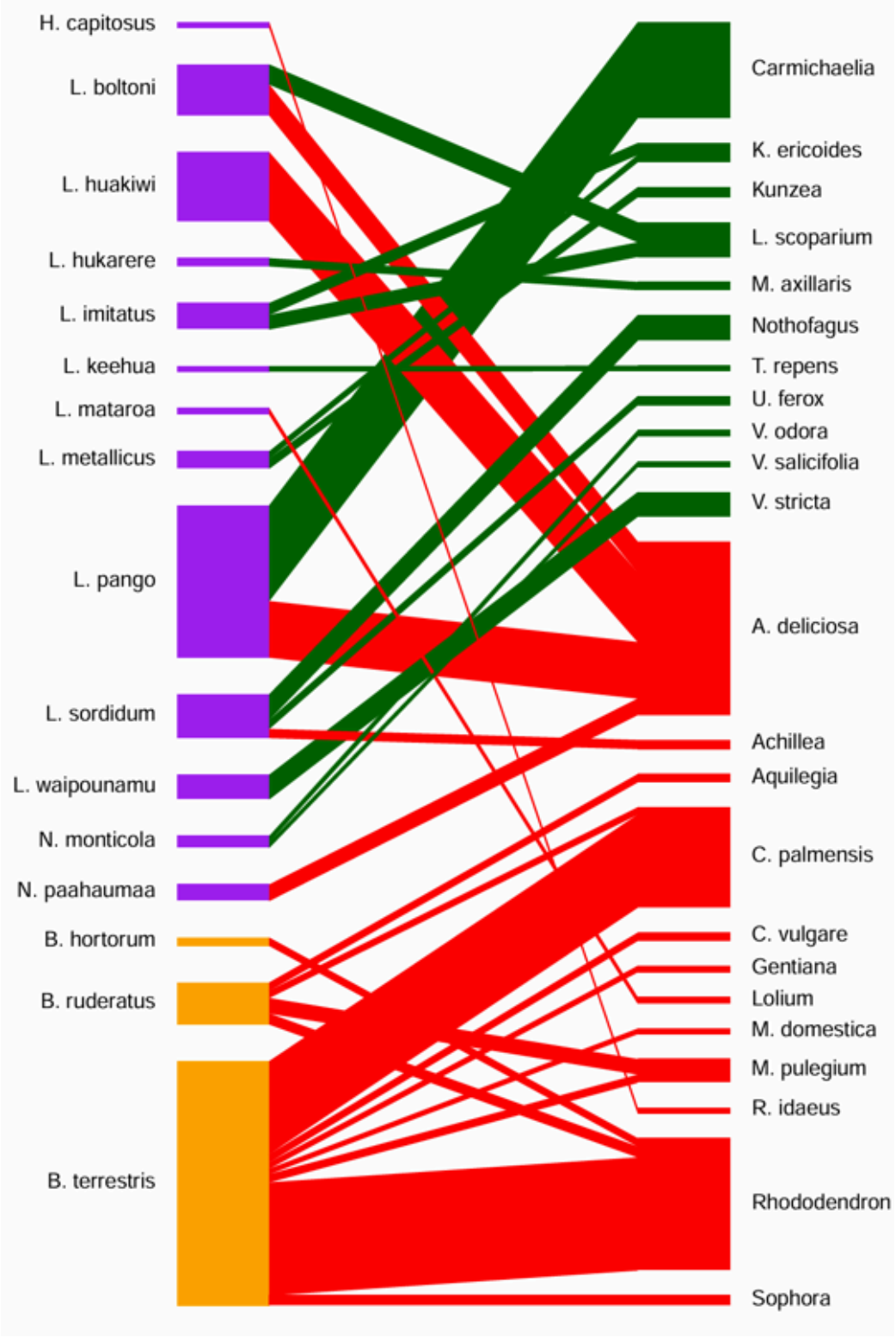


Figure 4

Bee-plant bipartite networks across exotic land cover types. Colours as for Figure 2.

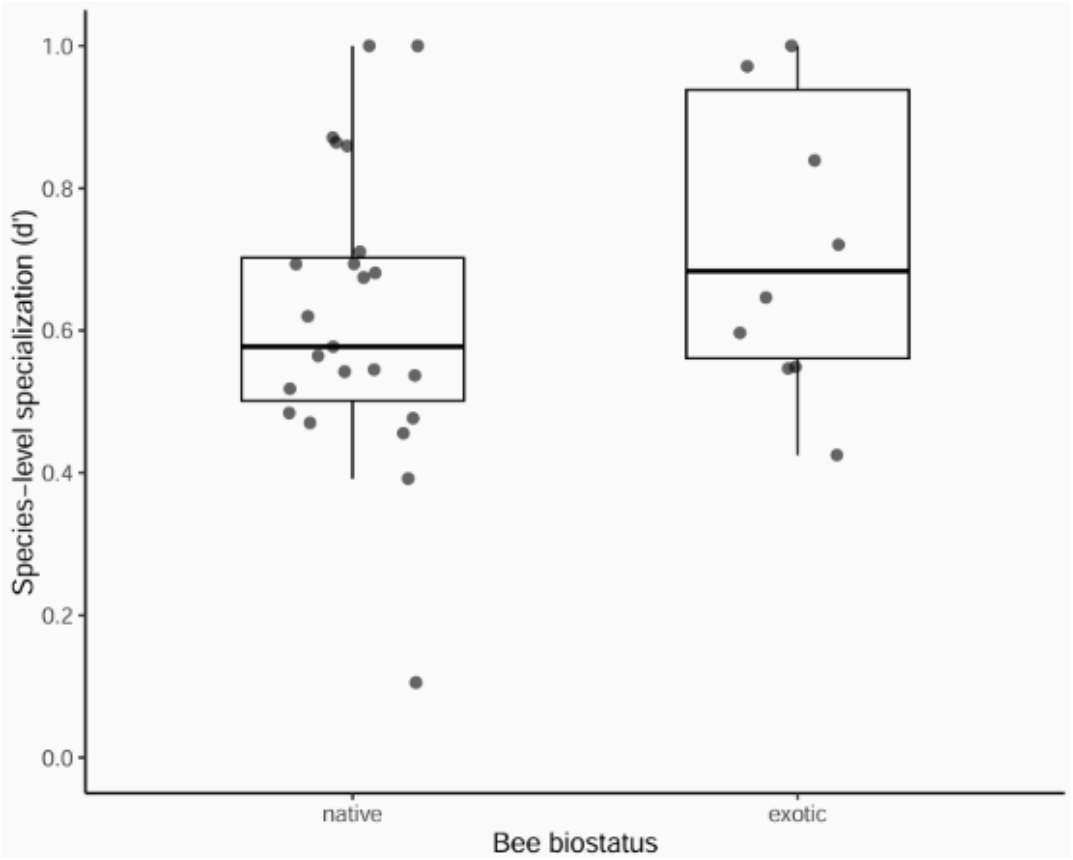


Figure 5

Species-level specialisation (d') of bee species grouped by biostatus (native vs exotic), with points representing individual bee species.

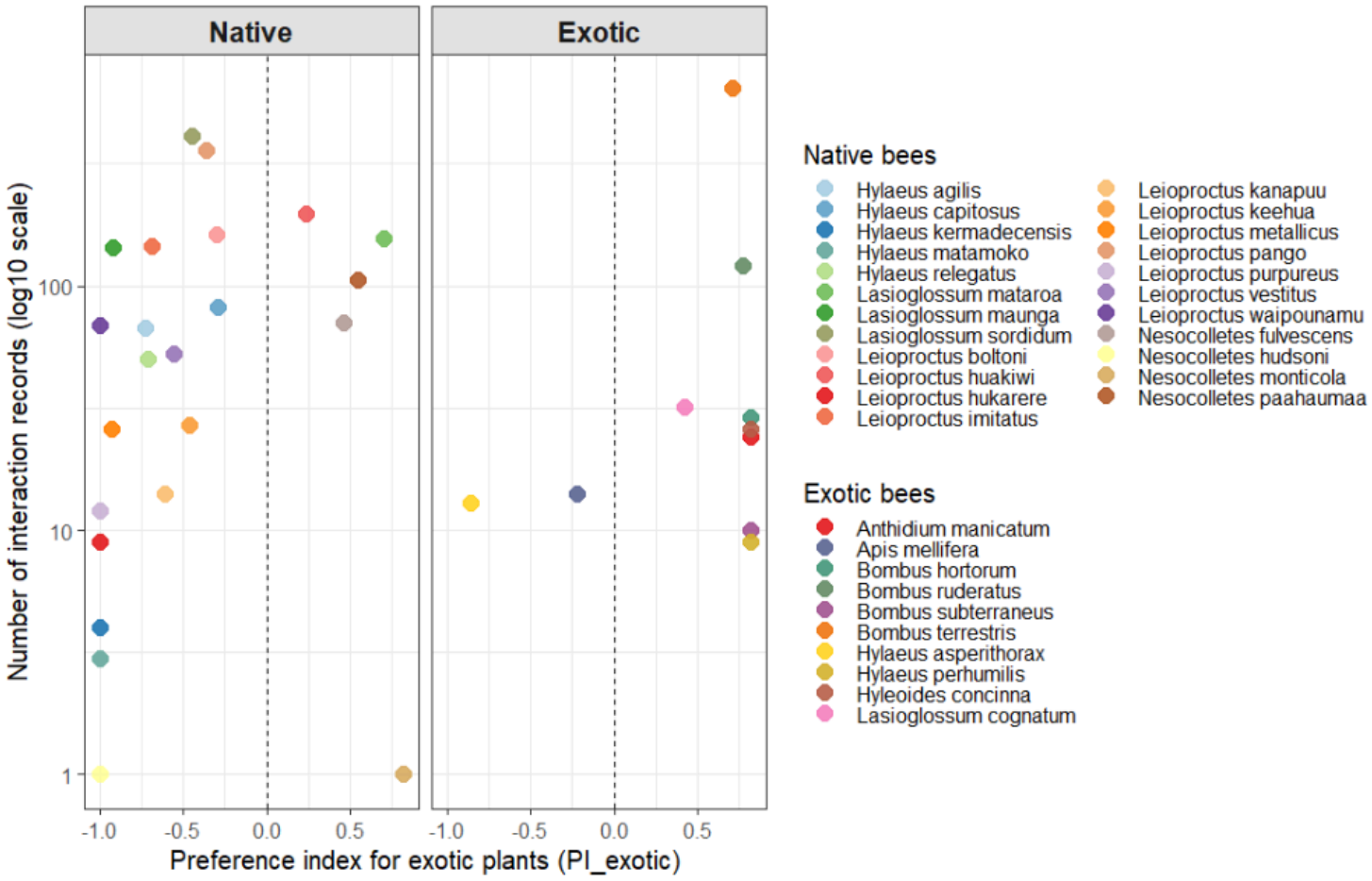


Figure 6

Preference index (PI_exotic) for exotic plants plotted against the number of interaction records for native and exotic bee species in native and exotic land cover (grey columns).

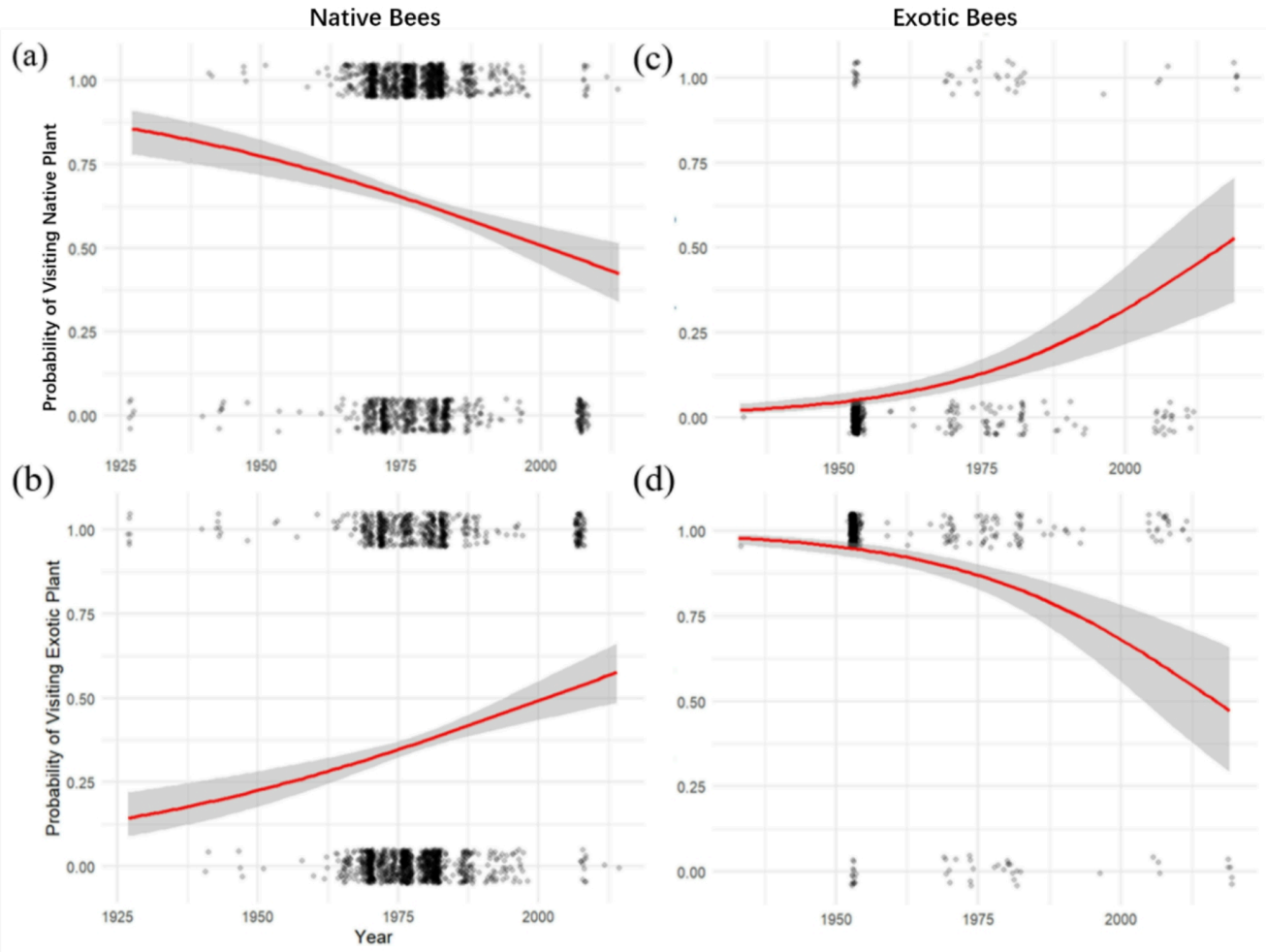


Figure 7

Predicted probabilities (±95% CI) from GLMs showing changes in bee-plant interactions over time. (a) native bees- native plants; (b) native bees-exotic plants; (c) exotic bees-native plants; (d) exotic bees-exotic plants.

Supplementary Files

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