

# Specialization of Mutualistic Interaction Networks Decreases toward Tropical Latitudes

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## Summary

Species-rich tropical communities are expected to be more specialized than their temperate counterparts [1–3]. Several studies have reported increasing biotic specialization toward the tropics [4–7], whereas others have not found latitudinal trends once accounting for sampling bias [8, 9] or differences in plant diversity [10, 11]. Thus, the direction of the latitudinal specialization gradient remains contentious. With an unprecedented global data set, we investigated how biotic specialization between plants and animal pollinators or seed dispersers is associated with latitude, past and contemporary climate, and plant diversity. We show that in contrast to expectation, biotic specialization of mutualistic networks is significantly lower at tropical than at temperate latitudes. Specialization was more closely related to contemporary climate than to past climate stability, suggesting that current conditions have a stronger effect on biotic specialization than historical community stability. Biotic specialization decreased with increasing local and regional plant diversity. This suggests that high specialization of mutualistic interactions is a response of pollinators and seed dispersers to low plant diversity. This could explain why the latitudinal specialization gradient is reversed relative to the latitudinal diversity gradient. Low mutualistic network specialization in the tropics suggests higher tolerance against extinctions in tropical than in temperate communities.

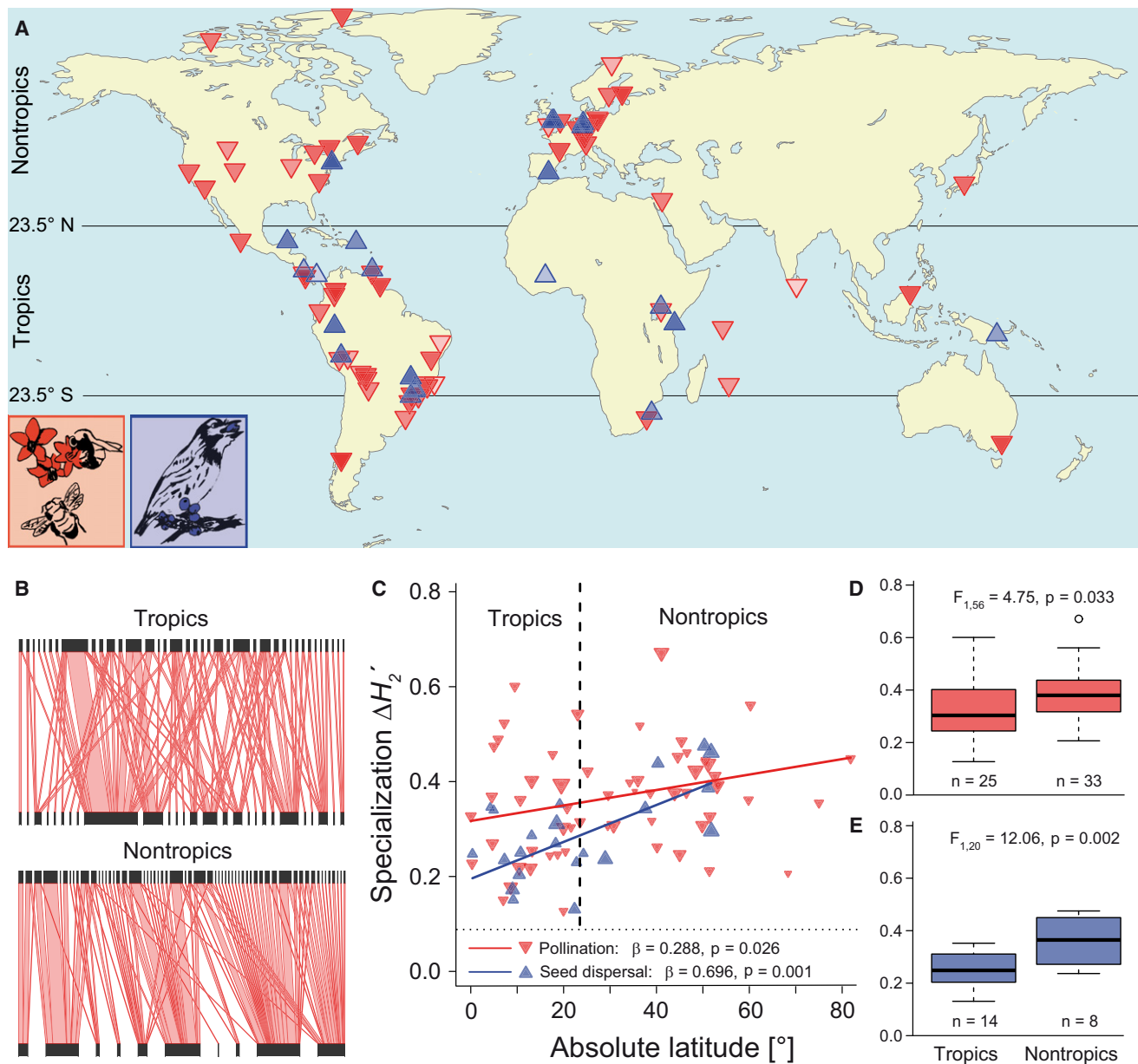
## Results and Discussion

### Latitudinal Specialization Gradient

In order to test the direction of the latitudinal specialization gradient, we gathered a global data set comprising a total of

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**Figure 1. Latitudinal Trends in Specialization of Pollination and Seed Dispersal Networks**

(A) Global distribution of pollination (red) and seed dispersal (blue) networks. Color intensities of triangles reflect mean network specialization ( $\Delta H_2'$ ) in each study region: color intensity increases with  $\Delta H_2'$ .

(B) Examples of a generalized pollination network with functionally redundant pollinators (top:  $\Delta H_2' = 0.18, 13^\circ\text{S}$ ) and a specialized network with functionally distinct pollinators (bottom:  $\Delta H_2' = 0.51, 51^\circ\text{N}$ ). Pollinators are shown at top and plants at bottom of the networks.

(C) The relationship between  $\Delta H_2'$  and latitude. Symbol size corresponds to weights by sampling intensity in each region.

(D and E) The difference in  $\Delta H_2'$  between tropical ( $\leq 23.5^\circ$ ) and nontropical ( $>23.5^\circ$ ) regions. Thick horizontal lines are medians, boxes indicate 25<sup>th</sup> and 75<sup>th</sup> percentiles, whiskers indicate the data range, and the circle is an outlier. See [Figure S1](#) for consistent latitudinal trends in alternative indices of biotic specialization and [Table S1](#) for an overview of the data set.

282 quantitative pollination and seed dispersal networks from 80 sampling regions (58 for pollination, 22 for seed dispersal) ranging in absolute latitude from  $0^\circ$  to  $82^\circ$  (Figures 1A and 1B; see also [Table S1](#) available online). Original studies reported the number of pollinator or seed disperser individuals feeding on a plant species or the number of individuals of a consumer species carrying pollen or seeds of a plant species. Although pollinator and seed disperser species differ in the efficiency of mutualistic services provided to plant species

[12, 13], because original studies did not report interaction efficiencies, we relied on estimates of interaction strength as a surrogate for the mutualistic importance of a consumer species for a plant species [12].

We estimated specialization of the interacting species by assessing patterns of niche partitioning and resource overlap among pollinator or seed disperser species [14–16]. We exploited recent advances in the analysis of quantitative interaction networks that facilitate the comparison of network-wide

### Latitudinal Trends in Biotic Specialization

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Table 1. Minimal Adequate Linear Models for Relationships between Network Specialization  $\Delta H_2'$  and Predictor Variables

Predictor	$\beta$	t	p
<b>Absolute Latitude (n = 80, <math>R^2 = 0.24</math>, <math>p &lt; 0.001</math>)</b>			
Network type (pollination)	0.122	2.70	0.009
Absolute latitude	0.696	3.40	0.001
Network type (pollination) $\times$ absolute latitude	-0.408	-1.67	0.098
<b>Past Climate Stability (n = 80, <math>R^2 = 0.19</math>, <math>p = 0.003</math>)</b>			
Network type (pollination)	0.160	3.09	0.003
Glaciated during LGM	0.072	1.95	0.055
Climate-change velocity	0.555	2.59	0.012
Network type (pollination) $\times$ climate-change velocity	-0.564	-2.36	0.021
<b>Contemporary Climate (n = 80, <math>R^2 = 0.27</math>, <math>p &lt; 0.001</math>)</b>			
Network type (pollination)	0.464	1.93	0.057
Growing degree days	-0.456	-4.54	<0.001
<b>Regional Plant Diversity (n = 78, <math>R^2 = 0.13</math>, <math>p = 0.004</math>)</b>			
Network type (pollination)	0.065	2.50	0.015
Regional plant diversity	-0.250	-2.13	0.036
<b>Local Plant Diversity (n = 232, <math>R^2</math> and p values not applicable for mixed effects models)</b>			
Network type (pollination)	0.058	1.96	0.052
Local plant diversity	-0.233	-2.49	0.014

Models correspond to relationships in [Figures 1C, 2, and 3](#). See [Figure S4](#) for spatial autocorrelation in model residuals and [Table S3](#) for independence of  $\Delta H_2'$  from sampling effort and network size. For analyses of latitude, past climate stability, contemporary climate, and regional plant diversity, least squares of linear models were weighted according to the sampling intensity within a region. For analysis of local plant diversity, we accounted for the spatial structure in the data by fitting mixed-effects models with region as random effect. For analyses of latitude, contemporary climate, and regional and local plant diversity, we compared five models (including main and interaction effects of the respective predictor variable and network type), and for analysis of past climate stability, we compared nine models (including main and interaction effects of climate-change velocity and network type plus the additional covariate glaciated during last glacial maximum [LGM]). Minimal adequate models were those with the lowest Akaike information criterion, corrected for small sample size, AICc.

specialization among communities differing in species richness [16]. This approach aims at integrating specialization across individual species to the community level, providing information about functional complementarity and redundancy among species [17]. The specialization metric gives more weight to frequently observed rather than rarely observed species and is weighted by interaction frequencies [16]. This mitigates potential biases in estimates of specialization by giving low weights to accidental observations of consumers on plants with which they are rarely associated.

We found that specialization of both pollination and seed dispersal networks decreased significantly toward tropical latitudes ([Figure 1C](#); [Table 1](#)). The same pattern was found in a categorical approach: specialization of both network types was significantly lower in the tropics than in temperate regions ([Figures 1D and 1E](#)); this pattern was also found when we restricted the analysis to the New World ( $F_{1,44} = 4.2$ ,  $p = 0.047$ ) or the Old World ( $F_{1,29} = 11.0$ ,  $p = 0.002$ ). We emphasize that alternative indices of biotic specialization (i.e., connectance, unweighted and weighted generality), as well as guild-specific analyses for plants and animals, showed corresponding latitudinal trends, all confirming a lower degree of specialization in the tropics ([Figure S1](#)). This finding contradicts the long-standing assumption that biotic

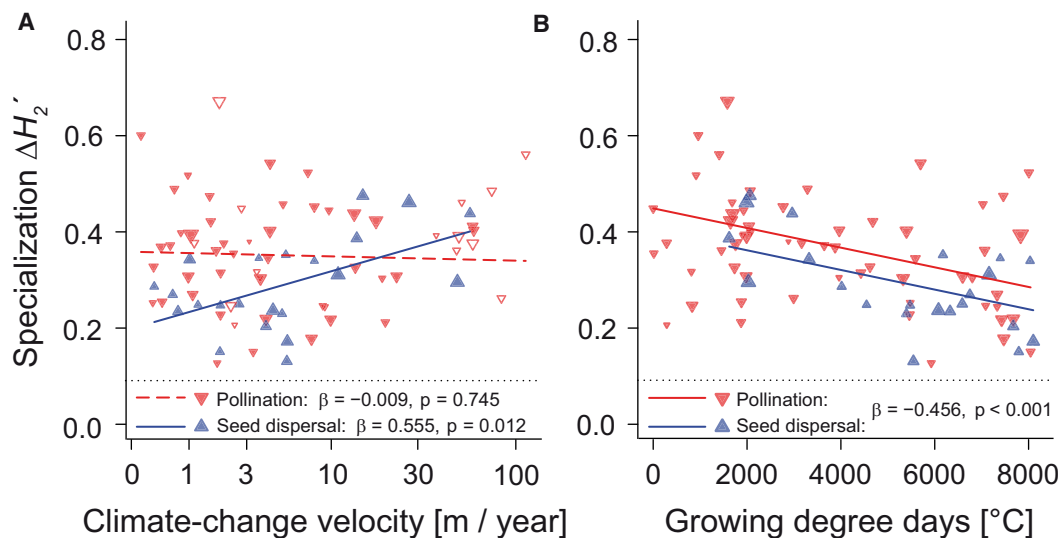
interactions are more specialized in species-rich tropical communities [1–7], which appears to be reversed for mutualistic interactions involving mobile pollinators and seed dispersers.

### Effects of Climate and Plant Diversity

In order to identify climatic factors that may determine the latitudinal specialization gradient, we tested for effects of past climate stability (i.e., climate-change velocity [18]) and contemporary climate on network specialization. To describe the latitudinal gradient in contemporary climate, we focused on cumulative annual temperature [19], which was closely associated with potential and actual evapotranspiration ([Figure S2](#)). Both past climate stability and contemporary climate have been postulated to influence biotic specialization [3, 5]. Past climate stability reflects the temporal stability of local communities and the available time for coevolution [20]. Effects of contemporary climate on network specialization might be mediated by an increase in plant diversity in warm climates [21] because high plant diversity reduces relative abundances and densities of resource species. Consistent with optimal foraging theory, reduced densities of resource plants lead to longer search times [22] and constrain the specialization of consumer species [23].

Specialization of seed dispersal networks increased with increasing climate-change velocity ([Figure 2A](#)), suggesting that coevolutionary processes have led to more generalized seed dispersal systems in regions with stable climates. This is in line with recent ideas that diffuse coevolutionary processes in mutualistic networks favor trait convergence [24]. On the other hand, specialization of pollination networks was unaffected by climate-change velocity ([Figure 2A](#)), possibly due to multiple trade-offs between the benefits of low and high degrees of specialization for the fitness of plants and pollinators that preclude general specialization trends over evolutionary timescales [25]. In contrast, increasing specialization with increasing past climate stability has been shown for plant-hummingbird networks [5]. Reasons for these divergent findings may include strong direct competition between hummingbirds [26] and tight coadaptations between hummingbirds and their food plants [27], leading to increased network specialization where species composition is relatively stable. Effects of past climate fluctuations on hummingbird range-size dynamics may have caused the breakup of coadapting plant-hummingbird species pairs in areas with low past climate stability [5, 20]. Other types of pollinators may be more flexibly linked to their resource plants [28], resulting in weak effects of community stability on network specialization.

Specialization of both pollination and seed dispersal networks consistently decreased with increasing cumulative annual temperature ([Figure 2B](#); [Table 1](#)). The effect of contemporary climate on network specialization was much stronger than that of past climate stability (cf.  $R^2$  values in [Table 1](#) and Akaike weights from multipredictor models in [Table S2](#)), showing that current conditions, rather than historical processes, have influenced associations among consumer and resource species in mutualistic networks. Consistent with the effect of contemporary climate, network specialization also decreased with increasing plant diversity both regionally and locally ([Figures 3A and 3B](#); [Table 1](#)). Differences in plant diversity and associated changes in relative resource abundances provide a generic explanation for decreasing network specialization with decreasing latitude because both regional



**Figure 2. Effects of Past Climate Stability and Contemporary Climate on Specialization of Pollination and Seed Dispersal Networks**

(A) Relationship between network specialization  $\Delta H_2'$  and climate-change velocity (m/year; log scale), i.e., climate stability from the LGM to contemporary climate. Open triangles indicate glaciated regions during the LGM.

(B) Relationship between network specialization  $\Delta H_2'$  and growing degree days (°C), i.e., current cumulative annual temperature.

See [Figure S2](#) for correlations between cumulative annual temperature and other climatic predictor variables and [Table S2](#) for multiple predictor models including past climate stability and contemporary climate.

and local plant species richness decreased with latitude ([Figure S3](#)). The latitudinal gradient in the diversity of animal-pollinated flowers and animal-dispersed fruits is even stronger than the overall plant diversity gradient [29]. Previous studies have shown that increasing plant diversity in the tropics is also associated with both a wider range of resource traits [4, 30] and a larger number of distinct pollination systems [11]. In response to high functional resource diversity, generalist consumer species may evolve traits [28, 30] that enable them to use resources from a wide trait spectrum [24], whereas consumer species associated with a specific pollination or seed dispersal syndrome may utilize various plant species within that syndrome [28, 30]. Consistent with previous work at the local scale [23], our findings suggest that high resource diversity may represent a key driver of generalization of consumer species in mutualistic networks.

#### Influence of Guild Structure and Network Sampling

Latitudinal trends in guild structure could also influence latitudinal differences in specialization. Whereas most tropical seed dispersers feed on fruits throughout the year, most seed dispersers in temperate systems switch diet between fruits and invertebrates [31]. Frugivore species appear to be more generalized than omnivores in seed dispersal networks [32]. In our data set, frugivores were more numerous in tropical than in temperate systems (ANOVA:  $F_{1,20} = 7.0$ ,  $p = 0.015$ ), and network specialization was negatively associated with their proportion in the network (Pearson correlation:  $r = -0.60$ ,  $p = 0.003$ ). Pollinator communities also differed between tropical and temperate latitudes: the proportion of long-lived pollinator species (vertebrate pollinators and social insects with perennial colonies, such as honeybees, stingless bees, and ants) was higher in tropical than in temperate systems (ANOVA:  $F_{1,51} = 79.7$ ,  $p < 0.001$ ). Long-lived species might use more different resources during their life span than short-lived species. The latitudinal difference in longevity, however,

could not be assigned unequivocally to network specialization (Pearson correlation:  $r = -0.26$ ,  $p = 0.056$ ). Differences in guild structure among tropical and temperate consumer communities may supplement effects of climate and plant diversity on network specialization, and future studies should aim at separating the relative role of changes in consumer communities from that of climate and plant diversity.

Despite the fact that we compiled the most comprehensive global database of quantitative mutualistic networks thus far, we are aware that the data set is heterogeneous, combining interaction data from different studies. We assessed the sensitivity of our results to potentially confounding latitudinal differences in network sampling. Specifically, we tested the effects of time span of observation (number of observation days), habitat type (forest versus nonforest habitats), and taxonomic completeness of sampling (entire species community versus single plant and/or animal family) together with the effects of past climate stability and contemporary climate on network specialization. This multipredictor analysis supported our conclusion that contemporary climate was the best predictor to explain the latitudinal specialization gradient ([Table S2](#)).

#### Conclusions

We found that specialization of pollination and seed dispersal networks decreases toward tropical latitudes. This finding calls for a careful rethinking of the role of specialized biotic interactions as a cause of high tropical diversity. Furthermore, we showed that past climate stability is related to specialization only in seed dispersal networks, whereas specialization in both pollination and seed dispersal networks is associated with contemporary climate and plant diversity. We propose that the latitudinal specialization gradient is to a large extent mediated by the latitudinal gradient in plant diversity because high resource diversity requires consumer species to generalize their diet.



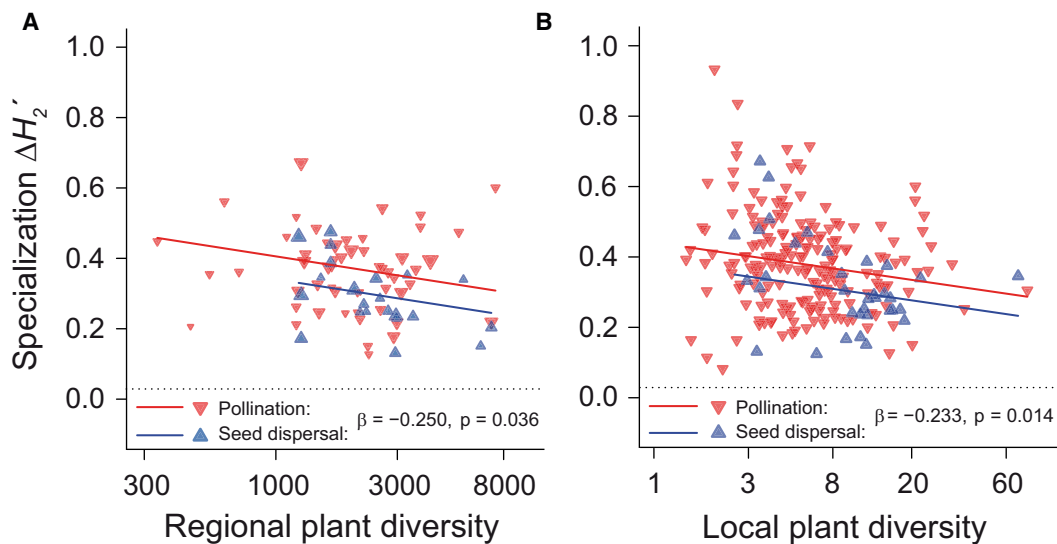


Figure 3. Effects of Regional and Local Plant Diversity on Specialization of Pollination and Seed Dispersal Networks

(A) Relationship between network specialization  $\Delta H_2'$  and regional plant diversity, i.e., the number of vascular plant species (log scale) in equal-area grids of  $\approx 12,100 \text{ km}^2$ .

(B) Relationship between network specialization  $\Delta H_2'$  and local plant diversity, i.e., the effective number of plant species (log scale) in each network ( $e$  to the power of Shannon diversity of plant species interaction frequencies).

Regional diversity of vascular plant species and average local plant diversity were not correlated ( $n = 78, r = 0.077, p = 0.505$ ). Regional plant diversity could not be derived for small islands ( $< 2,000 \text{ km}^2$ , i.e., Seychelles and Mauritius were excluded from this part of the analysis) and was set to the species pool of the entire Canadian Arctic Archipelago (340 species) for the northernmost point (Ellesmere Island). See Figure S3 for negative latitudinal trends in regional and local plant diversity.

Our findings also have important implications for the robustness of pollination and seed dispersal functions to disturbance in tropical and temperate ecosystems. Low specialization of tropical plant-animal communities is likely to increase their functional redundancy and resistance against secondary extinctions [33], whereas high diversity and functional complementarity of consumer species may be crucial for maintaining ecosystem functions in the more specialized temperate communities [17].

## Experimental Procedures

### Network Metrics

For each of the 282 networks, interactions among animal and plant species were summarized in a bipartite interaction matrix between  $I$  animal species in rows and  $J$  plant species in columns (data collection is described in the Supplemental Experimental Procedures). Species represent the nodes of the network, and interaction strength per link is given by the number of interaction events between an animal and a plant species. All network analyses were performed with the software R [34] and the bipartite 1.17 package [35].

To quantify specialization for a weighted network, we first calculated interaction diversity (Shannon entropy)  $H_2$  across all  $I$  animal and  $J$  plant species [36]. In order to disentangle different degrees of specialization from differences in species frequencies, a standardized network specialization metric has been proposed, in which the actual  $H_2$  value is compared with the range ( $H_{2\min}$  to  $H_{2\max}$ ) of possible  $H_2$  from any distribution of interaction events with the same number of events per species [36].  $H_2'$  ranges from 0.0 for the most generalized (i.e., maximum niche overlap) to 1.0 for the most specialized network (i.e., maximum niche divergence). In poorly sampled networks, higher values of  $H_2'$  can be reached by chance as expected values of nonselective foraging deviate more strongly from 0 and may get closer to 1 [36]. Because we aimed at comparing the most unbiased estimates of network specialization, we used a modified specialization index  $\Delta H_2' = H_2' - H_{2\text{ran}}$ , where  $H_{2\text{ran}}$  represents the mean  $H_2'$  from 1,000 randomized networks. Randomizations were performed with the Patefield algorithm, which randomly redistributes interaction events among all cells of the network while constraining total interaction

strength per species.  $\Delta H_2'$  differs only slightly from  $H_2'$ , and the latitudinal trends in both metrics were qualitatively identical (compare Figures 1C and S1A).

We also examined latitudinal trends in biotic specialization with other specialization indices. We calculated two alternative indices for binary networks: connectance, i.e., the realized proportion of possible links, and unweighted generality, i.e., the average number of links (species degree) per consumer species. We also determined weighted generality, i.e., the average effective number of links per consumer species, accounting for interaction strength [35]. Furthermore, we tested specialization trends separately for plants and animals by calculating weighted and unweighted means of species-level specialization  $d'$  [36]. Because network asymmetry, i.e., the balance between plant and animal diversity in a network, strongly affects guild-level specialization [16], we accounted for differences in network asymmetry, i.e., we included network asymmetry as a covariate in guild-level analyses. In the main manuscript, we focus on  $\Delta H_2'$  because it integrates specialization across the entire community [16] and was the only metric that was affected by neither the number of interaction events nor the number of species in the network (Table S3).

### Predictor Variables

For each network location, we obtained climate-change velocity since the last glacial maximum (LGM, 21,000 years ago) as an estimate of past climate stability [18]. The measure describes the rate at which temperature conditions have moved over the Earth's surface since the LGM (here in m/year), based on 2.5 min resolution maps of contemporary climate [37] and paleoclimate projections (CCSM3 model in [38]). The spatial pattern of climate-change velocity since the LGM is representative of the last several hundred thousand years [39]. We also identified locations that were glaciated at the LGM with maps of glacial extent [40]. We additionally obtained information on contemporary climate (monthly temperatures, annual precipitation) for each network location at a 2.5 min resolution [37]. We calculated estimates of the cumulative annual temperature above  $5^\circ\text{C}$  (i.e., growing degree days) as a measure of available thermal energy during the growing season [19]. The regional plant diversity for each network location was derived from spatial interpolation of global plant richness data at a spatial resolution of  $\approx 12,100 \text{ km}^2$  [21]. The local plant diversity was derived from each network as the Shannon index of the plant species marginal totals. This takes into account the number of observed plant species in a network

and the evenness of their abundance distribution. Local plant diversity was averaged over networks from the same location ( $n = 232$  locations).

#### Statistical Analyses

Each of the 282 networks was assigned to a sampling region ( $n = 80$  regions). Regions were defined by the original studies that focused on a particular habitat type in a given area (see [Supplemental Experimental Procedures](#)). Region-level analyses were conservative because they prevented pseudoreplication of networks with almost identical climatic conditions and overrepresentation of regions with many replicate networks.

At the global scale, we related network specialization  $\Delta H_2'$  to absolute latitude, past climate stability, contemporary climate, and regional plant diversity in linear models. We used the sampling region as the unit of replication and calculated mean  $\Delta H_2'$  of all networks within a region. At the local scale, we tested the effect of local plant diversity on  $\Delta H_2'$  with a random-intercept model with sampling region as random factor. For each predictor, we fitted reduced and full models (including main effects and interaction effects with network type) and identified the minimal adequate model according to the lowest Akaike information criterion, corrected for small sample size, AICc ([Table 1](#)).

In analyses at the global scale, we accounted for differences in sampling intensities among regions with least squares weighted by sampling intensity,

$$Intensity_{web} = \frac{\sqrt{N_i}}{\sqrt{size_i}};$$

$$Intensity_{region} = \log_{10}(Intensity_{web\_mean} \times \sqrt{n} + 1),$$

where  $N_i$  is the number of interactions in network  $i$  and  $size_i$  is the product of the number of plant species and the number of animal species in network  $i$ .  $Intensity_{web}$  reflects the number of interactions observed per species. Sampling intensity per region ( $Intensity_{region}$ ) combines mean network sampling intensity in a region ( $Intensity_{web\_mean}$ ) with the number of networks sampled per region ( $n$ ). Analyses of the relationship between  $\Delta H_2'$  and latitude with each network as a replicate ( $\beta = 0.262$ ,  $p < 0.001$ ) and with unweighted least squares at the regional scale ( $\beta = 0.326$ ,  $p = 0.003$ ) resulted in the same latitudinal trend as the weighted regional analysis. We visually examined spatial dependences (Moran's  $I$ ) in the residuals of all minimal adequate models. Spatial autocorrelation was negligibly small in all cases ([Figure S4](#)).

#### Supplemental Information

Supplemental Information includes four figures, three tables, and Supplemental Experimental Procedures and can be found with this article online at <http://dx.doi.org/10.1016/j.cub.2012.08.015>.

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## Supplemental Information

### Specialization of Mutualistic Interaction Networks Decreases toward Tropical Latitudes

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## Supplemental Inventory

### 1. Supplemental Data

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### 2. Supplemental Experimental Procedures

Data set description

Author contributions

Extended acknowledgments

### 3. Supplemental References



## 1. Supplemental Data

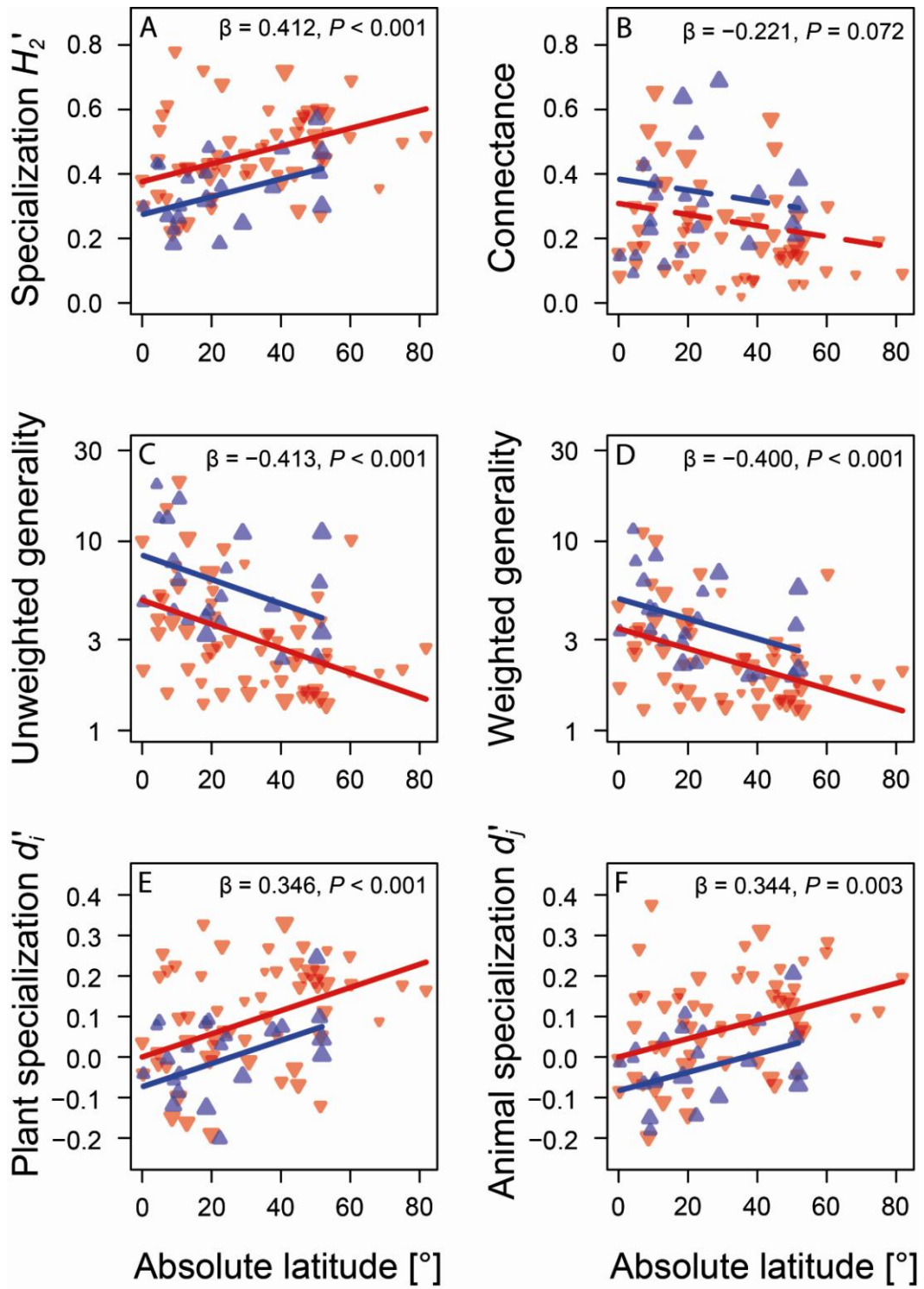
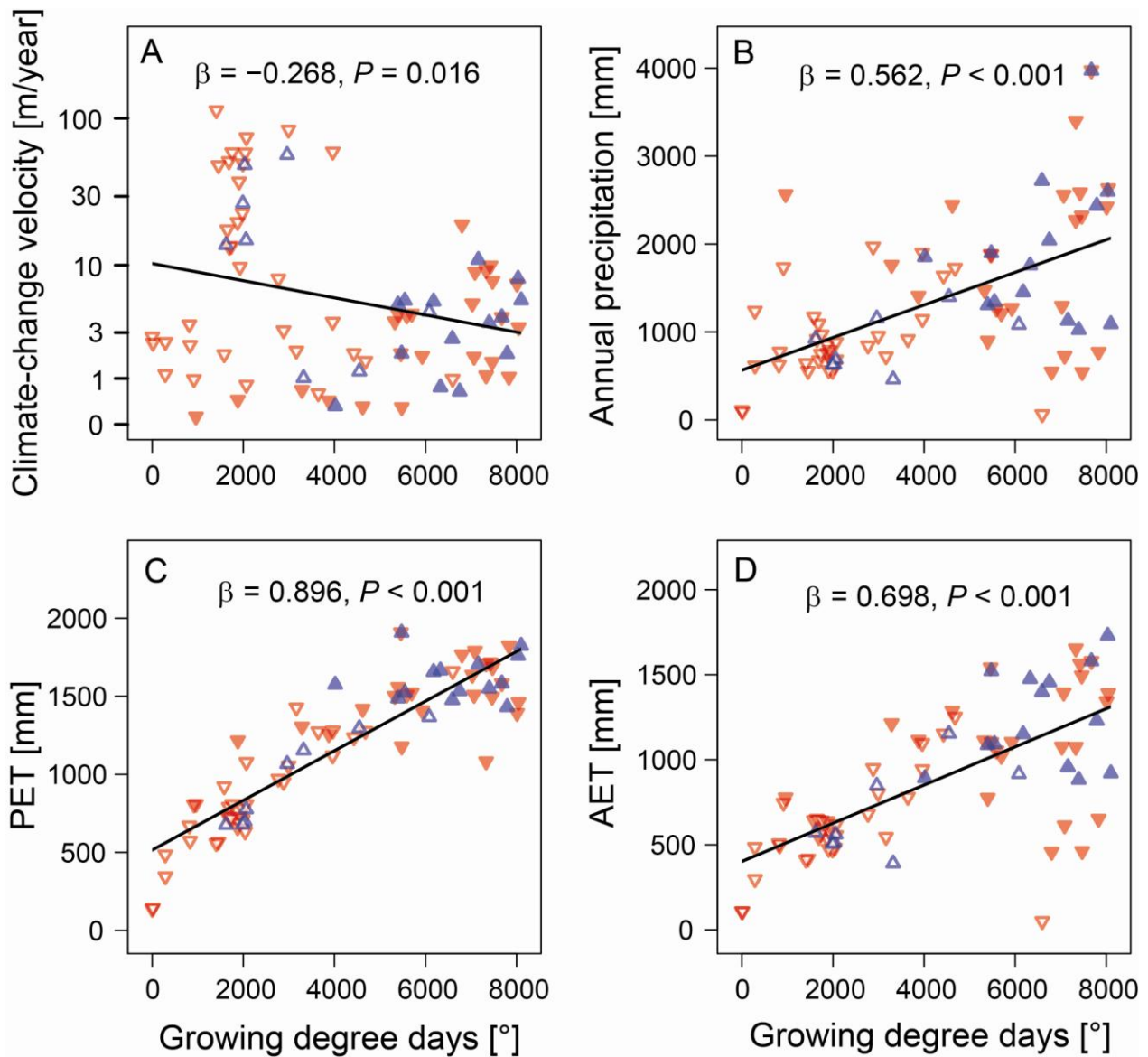


Figure S1.

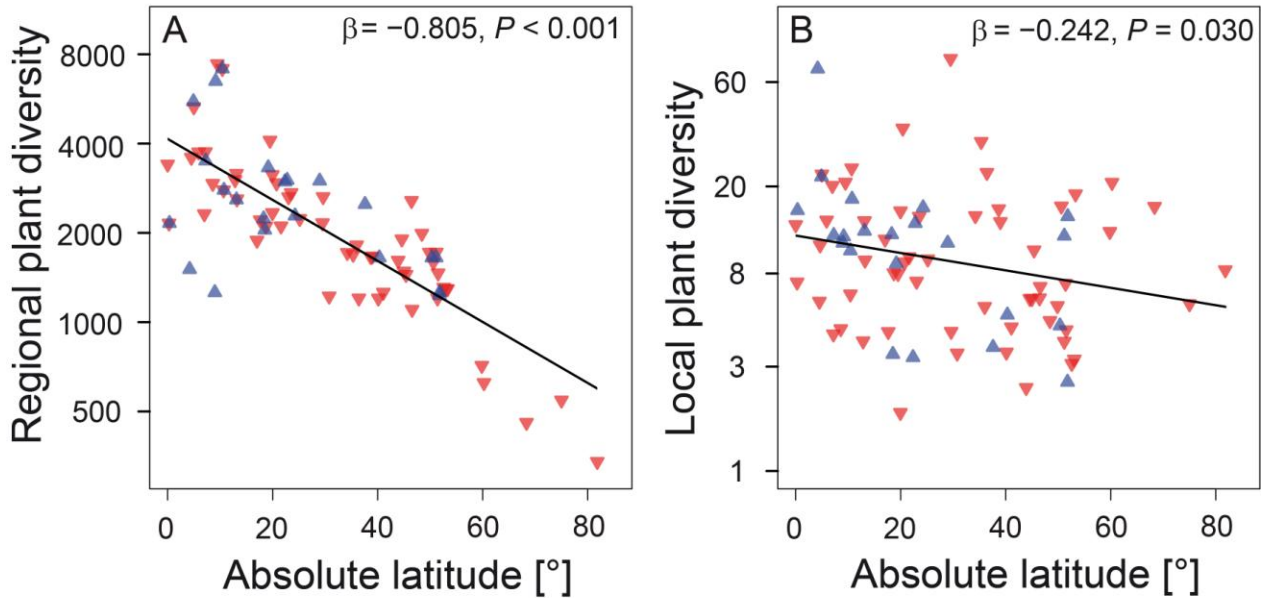
**Figure S1, Related to Figure 1. Latitudinal Specialization Trends in Standardized and Unstandardized Network Metrics**

(A) Network specialization  $H_2'$ , i.e., standardized Shannon entropy, (B) connectance, i.e., the realized proportion of possible links, (C) unweighted generality, i.e., the average number of links (the number of observed resource plant species) per consumer species, (D) weighted generality, i.e., the average effective number of links per consumer species (accounting for interaction strength), (E) plant specialization  $d_i'$ , and (F) animal specialization  $d_j'$ . For (E) and (F) partial residuals are shown because regression models were adjusted for the effects of mean web asymmetry on plant and animal specialization in each region; web asymmetry was given as the difference between the effective number of plant and animal species standardized by the sum of the effective number of plant and animal species. Results for (E) and (F) were qualitatively identical for weighted and unweighted means of  $d'$ , shown are weighted means across species. Symbol size corresponds to weights by sampling intensity in each region. We focus on a null-model adjusted version of (A) in the main text because it was the only metric that was independent of sampling effort and network size (Table S3). All network metrics showed the same trend: Tropical communities were more generalized than temperate communities.



**Figure S2, Related to Figure 2. Relationships between Cumulative Annual Temperature (Growing Degree Days) and Other Climatic Variables**

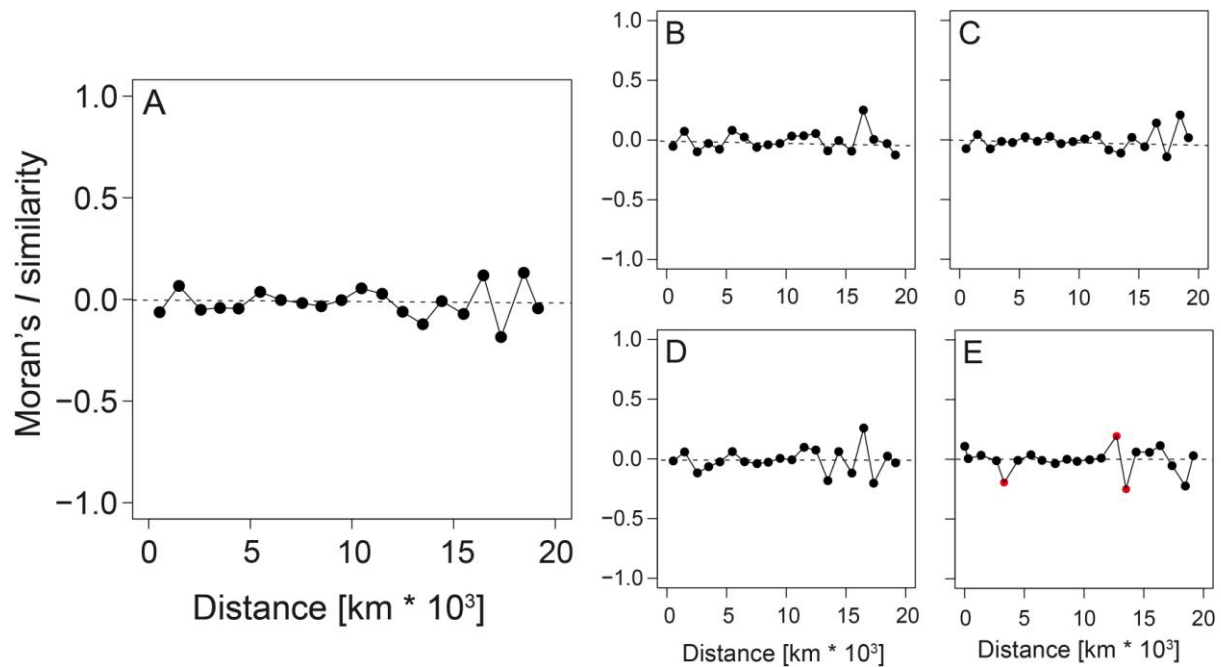
(A) Climate-change velocity (log10-scale), (B) annual precipitation, (C) potential evapotranspiration (PET) and (D) actual evapotranspiration (AET). Red triangles indicate regions with pollination networks, blue triangles regions with seed dispersal networks. Filled triangles indicate tropical regions, open triangles indicate non-tropical regions. Cumulative annual temperature is closely related to gradients in annual precipitation, AET and PET, probably because climates in most study regions were not limited by water availability. Values for potential (PET) and actual evapotranspiration (AET) were taken from a global aridity database (<http://www.cgiar-csi.org/data/item/51-global-aridity-and-pet-database>).



**Figure S3, Related to Figure 3. Relationship between Plant Diversity and Latitude in the 80 Study Regions**

(A) Regional plant diversity, i.e., the number of vascular plant species (log<sub>10</sub>-scale) in equal area grids of  $\approx 12,100 \text{ km}^2$ .

(B) Mean local plant diversity, i.e., the effective number of plant species in each network ( $e$  to the power of Shannon diversity of plant species interaction frequencies), averaged over multiple networks from the same region. Red triangles indicate regions with pollination networks, blue triangles those with seed dispersal networks. Note that the estimates of regional plant species richness are likely to underestimate the latitudinal gradient in the diversity of animal-pollinated and animal-dispersed plants: while the proportions of animal-pollinated and animal-dispersed plants increase in the tropics [29], we relied on overall estimates of vascular plant species richness for this analysis. Regional and average local plant diversity were not correlated ( $n = 78, r = 0.077, p = 0.505$ ).



**Figure S4, Related to Table 1. Spatial Autocorrelation in the Residuals of Minimal Adequate Linear Models**

(A) Absolute latitude, (B) past climate stability, (C) contemporary climate, (D) regional plant diversity, and (E) local plant diversity. Minimal adequate linear models are provided in Table 1. Note that similarity in the residuals of all models did not decrease with increasing distance of discrete distance classes of 500 km, i.e., spatial autocorrelation was negligibly small in all minimal adequate models. Red dots indicate Moran's *I* similarities significantly different from 0 (two-sided permutation test,  $p < 0.025$ ).



**Table S1, Related to Figure 1. Detailed Information about Location and Sampling Intensity for Each of the 80 Sampling Regions**

For each sampling region, we provide the name of the data holders, network type (pollination or seed dispersal), latitude and longitude [decimal degrees], country, altitude [m above sea level], glaciation at last glacial maximum (21,000 years ago), predominant habitat type (forest or non-forest), completeness of sampling (full species communities or restricted to specific plant and/or animal families), sampling focus (plant or animal) and sampling design (sampling time representative for species abundance or standardized per species). We further provide the number of networks per region and means across all networks from a region for sampling duration [observation days], number of animal and plant species, number of observed interaction events as well as network specialization  $\Delta H_2'$ .

Table S1

Region_ID	Data holder	Network type	Latitude	Longitude	Country	Altitude	Glaciation LGM	Habitat	Completeness	Focus	Design
P_1	Abrahamczyk	pollination	-17.0	-65.1	Bolivia	302	no	forest	full	plant	standardized
P_2	Abrahamczyk	pollination	-17.6	-63.4	Bolivia	411	no	forest	full	plant	standardized
P_3	Abrahamczyk	pollination	-18.7	-63.2	Bolivia	434	no	forest	full	plant	standardized
P_4	Abrahamczyk	pollination	-21.6	-62.5	Bolivia	268	no	forest	full	plant	standardized
P_5	Alarcon	pollination	39.0	-107.0	USA	3420	yes	non-forest	full	plant	representative
P_6	Alarcon	pollination	34.2	-117.0	USA	2300	no	non-forest	full	plant	representative
P_7	Albrecht	pollination	46.4	9.9	Switzerland	1984	yes	non-forest	full	plant	representative
P_8	Bommarco	pollination	59.8	17.5	Sweden	20	yes	non-forest	full	plant	representative
P_9	Barrett	pollination	46.6	-66.0	Canada	120	yes	forest	full	plant	standardized
P_10	Bauer	pollination	45.0	-109.4	USA	3050	yes	non-forest	restricted	plant	representative
P_11	Bazarian	pollination	-23.0	-48.1	Brasil	700	no	forest	full	plant	standardized
P_12	Bluethgen	pollination	53.1	13.9	Germany	30	yes	non-forest	full	plant	representative
P_13	Bluethgen	pollination	51.2	10.4	Germany	350	no	non-forest	full	plant	representative
P_14	Bluethgen	pollination	48.4	9.5	Germany	800	no	non-forest	full	plant	representative
P_15	Dalsgaard	pollination	19.5	-105.1	Mexico	265	no	forest	restricted	plant	representative
P_16	Dalsgaard	pollination	10.7	-61.3	Trinidad	185	no	forest	restricted	plant	representative
P_17	Dalsgaard	pollination	9.5	-83.5	Costa Rica	3150	no	forest	restricted	plant	representative
P_18	Dalsgaard	pollination	5.9	-73.4	Colombia	2400	no	forest	restricted	plant	representative
P_19	Dalsgaard	pollination	4.5	-73.9	Colombia	2475	no	forest	restricted	plant	representative
P_20	Dalsgaard	pollination	0.0	-78.8	Ecuador	1650	no	forest	restricted	plant	representative
P_21	Dalsgaard	pollination	-8.6	-38.6	Brasil	321	no	forest	restricted	plant	representative
P_22	Dalsgaard	pollination	-13.1	-41.6	Brasil	940	no	forest	restricted	plant	representative
P_23	Dalsgaard	pollination	-20.0	-43.9	Brasil	1325	no	forest	restricted	plant	representative
P_24	Dalsgaard	pollination	-20.8	-42.9	Brasil	785	no	forest	restricted	plant	representative
P_25	Dalsgaard	pollination	-23.5	-45.9	Brasil	850	no	forest	restricted	plant	representative
P_26	Dicks	pollination	52.6	1.3	UK	20	no	non-forest	full	plant	representative
P_27	Dworschak	pollination	5.0	117.8	Malaysia	100	no	forest	full	plant	representative
P_28	Elberling	pollination	68.3	18.5	Sweden	1000	yes	non-forest	full	plant	representative
P_29	Fruend	pollination	49.9	10.2	Germany	308	no	non-forest	full	plant	representative
P_30	Gotlieb	pollination	30.8	35.3	Israel	-155	no	non-forest	full	plant	representative
P_31	Hagen	pollination	0.3	34.9	Kenya	1600	no	forest	full	plant	representative
P_32	Harter	pollination	-29.5	-50.2	Brasil	750	no	forest	full	plant	representative
P_33	Holzschuh	pollination	51.5	9.9	Germany	150	no	non-forest	full	plant	representative
P_34	Inouye	pollination	-36.4	148.3	Australia	1990	no	non-forest	full	plant	representative
P_35	Kaepylae	pollination	60.2	22.0	Finland	25	yes	non-forest	restricted	plant	representative
P_36	Kaiser-Bunbury	pollination	-4.7	55.5	Seychelles	460	no	non-forest	full	plant	standardized
P_37	Kaiser-Bunbury	pollination	-20.4	57.5	Mauritius	650	no	non-forest	full	plant	standardized
P_38	Kato	pollination	35.3	135.9	Japan	350	no	forest	full	plant	representative
P_39	Kevan	pollination	81.8	-71.3	Canada	300	yes	non-forest	full	plant	representative
P_40	Koeniger	pollination	7.0	80.0	Sri Lanka	50	no	non-forest	restricted	animal	representative
P_41	Memmott	pollination	51.4	-2.6	UK	65	no	non-forest	full	plant	representative
P_42	Mosquin	pollination	75.0	-115.0	Canada	100	no	non-forest	full	plant	representative
P_43	Motten	pollination	36.0	-78.9	USA	100	no	forest	full	plant	representative
P_44	Ollerton	pollination	-29.6	30.1	South Africa	1200	no	non-forest	restricted	plant	representative
P_45	Poursin	pollination	44.6	1.1	France	230	no	non-forest	restricted	animal	representative
P_46	Queiroz	pollination	-25.2	-48.8	Brasil	150	no	forest	restricted	plant	representative
P_47	Reader	pollination	43.9	-80.4	Canada	490	yes	non-forest	restricted	plant	standardized
P_48	Schemeske	pollination	40.1	-88.2	USA	220	yes	forest	full	plant	representative
P_49	Small	pollination	45.4	-75.5	Canada	70	yes	non-forest	full	plant	representative
P_50	Ssymank	pollination	53.3	13.7	Germany	75	yes	non-forest	restricted	plant	representative
P_51	Ssymank	pollination	50.6	7.1	Germany	160	no	non-forest	restricted	plant	representative
P_52	Stiles	pollination	10.4	-84.0	Costa Rica	50	no	forest	restricted	plant	representative
P_53	Varassin	pollination	-20.0	-40.5	Brasil	700	no	forest	restricted	plant	representative
P_54	Vazquez	pollination	-41.1	-71.5	Argentina	969	yes	forest	full	plant	representative
P_55	Watts	pollination	-12.9	-69.4	Peru	260	no	forest	full	plant	standardized
P_56	Watts	pollination	-13.2	-72.2	Peru	3526	no	forest	restricted	plant	representative
P_57	Williams	pollination	38.7	-122.2	USA	203	no	non-forest	restricted	plant	representative
P_58	Williams	pollination	7.2	-58.6	Guyana	35	no	forest	full	plant	representative

Table S1 (continued)

Region_ID	Data holder	# networks	mean duration [days]	mean # animals	mean # plants	mean # interactions	$\Delta H_2'$	Further information
P_1	Abrahamczyk	2	4	26	16	72	0.24	S. Abrahamczyk, J. Kluge, Y. Gareca, S. Reichle, M. Kessler, <i>Plos One</i> 6, e27115 (2011).
P_2	Abrahamczyk	2	4	27	8	78	0.46	S. Abrahamczyk, J. Kluge, Y. Gareca, S. Reichle, M. Kessler, <i>Plos One</i> 6, e27115 (2011).
P_3	Abrahamczyk	1	4	27	11	143	0.25	S. Abrahamczyk, J. Kluge, Y. Gareca, S. Reichle, M. Kessler, <i>Plos One</i> 6, e27115 (2011).
P_4	Abrahamczyk	1	4	45	16	346	0.30	S. Abrahamczyk, J. Kluge, Y. Gareca, S. Reichle, M. Kessler, <i>Plos One</i> 6, e27115 (2011).
P_5	Alarcon	1	35	136	41	2111	0.32	R. Alarcón, thesis, University of California, Riverside, USA (2004).
P_6	Alarcon	1	39	127	38	1711	0.40	R. Alarcón, N. M. Waser, J. Ollerton, <i>Oikos</i> 117, 1796 (2008).
P_7	Albrecht	5	72	27	12	81	0.38	M. Albrecht, M. Riesen, B. Schmid, <i>Oikos</i> 119, 1610 (2010).
P_8	Bommarco	4	74	23	22	96	0.36	C. Westphal <i>et al.</i> , <i>Ecol. Monogr.</i> 78, 653 (2008).
P_9	Barrett	1	150	102	12	550	0.46	S. C. H. Barrett, K. Helenurm, <i>Can. J. Bot.</i> 65, 2036 (1986).
P_10	Bauer	1	61	11	7	453	0.25	P. J. Bauer, <i>Am. J. Bot.</i> 70, 134 (1983).
P_11	Bazarian	9	4	49	19	452	0.54	S. V. Bazarian, thesis, Universidade de São Paulo, São Paulo, Brazil (2010).
P_12	Bluethgen	23	1	37	8	157	0.39	Data collected by C. N. Weiner, M. Werner, and N. Blüthgen (coauthors) in 2008 in the Schorfheide Biosphere Reserve, Germany.
P_13	Bluethgen	36	1	39	9	224	0.44	Data collected by C. N. Weiner, M. Werner, and N. Blüthgen (coauthors) in 2008 in the Hainich National Park, Germany.
P_14	Bluethgen	66	1	47	12	269	0.42	C. N. Weiner, M. Werner, K. E. Linsenmair, N. Blüthgen, <i>Basic Appl. Ecol.</i> 12, 292 (2011).
P_15	Dalsgaard	1	365	5	15	6133	0.39	M. C. Arizmendi, J. F. Ornelas, <i>Biotropica</i> 22, 172 (1990).
P_16	Dalsgaard	1	365	9	57	1417	0.36	B. K. Snow, D. W. Snow, <i>J. Anim. Ecol.</i> 41, 471 (1972).
P_17	Dalsgaard	1	8	5	25	137	0.60	L. L. Wolf, F. G. Stiles, F. R. Hainsworth, <i>J. Anim. Ecol.</i> 45, 349 (1976).
P_18	Dalsgaard	1	25	12	22	343	0.49	D. W. Snow, B. K. Snow, <i>Bull. Br. Mus. (Nat. Hist.) Zool.</i> 38, 105 (1980).
P_19	Dalsgaard	1	23	9	13	304	0.37	D. W. Snow, B. K. Snow, <i>Bull. Br. Mus. (Nat. Hist.) Zool.</i> 38, 105 (1980).
P_20	Dalsgaard	1	70	19	65	2162	0.33	B. A. Walther, H. Brieschke, <i>Int. J. Ornithol.</i> 4, 115 (2001).
P_21	Dalsgaard	1	365	4	7	264	0.18	F. C. Leal, A. V. Lopes, I. C. Machado, <i>Rev. Bras. Bot.</i> 29, 379 (2006).
P_22	Dalsgaard	1	365	7	28	2519	0.40	C. G. Machado, <i>Zoologia</i> 26, 255 (2009).
P_23	Dalsgaard	1	365	6	10	775	0.30	M. F. Vasconcelos, J. A. Lombardi, <i>Ararajuba</i> 7, 71 (1999).
P_24	Dalsgaard	1	365	8	14	178	0.34	C. R. M. Abreu, M. F. Vieira, <i>Lundiana</i> 5, 129 (2004).
P_25	Dalsgaard	1	37	6	25	250	0.31	D. W. Snow, B. K. Snow, <i>El Hornero</i> 12, 286 (1986).
P_26	Dicks	2	12	49	17	2065	0.41	L. V. Dicks, S. A. Corbet, R. F. Pywell, <i>J. Anim. Ecol.</i> 71, 32 (2002).
P_27	Dworschak	1	90	30	43	1702	0.47	K. Dworschak, N. Blüthgen, <i>Ecol. Entomol.</i> 35, 216 (2010).
P_28	Elberling	1	120	118	23	383	0.21	H. Elberling, J. M. Olesen, <i>Ecography</i> 22, 314 (1999).
P_29	Fruend	21	1	23	11	76	0.31	J. Fründ, K. E. Linsenmair, N. Blüthgen, <i>Oikos</i> 119, 1581 (2010).
P_30	Gotlieb	4	90	16	6	205	0.31	Data collected by A. Gotlieb (coauthor) in 2009 in the Rift Valley, Israel.
P_31	Hagen	3	365	55	28	1028	0.23	M. Hagen, M. Kraemer, <i>Biol. Conserv.</i> 143, 1654 (2010).
P_32	Harter	1	365	185	184	5001	0.31	B. Harter, thesis, University of Tübingen, Germany (1999).
P_33	Holzschuh	4	60	8	9	70	0.33	Data collected by A. Holzschuh, C.F. Dormann, T. Tschardt (coauthors) in 2006 in the surroundings of Göttingen, Germany.
P_34	Inouye	1	82	83	41	1459	0.52	D. W. Inouye, G. H. Pyke, <i>Aust. J. Ecol.</i> 13, 191 (1988).
P_35	Kaepylae	1	150	5	34	211	0.56	M. Käpylä, <i>Biological Research Reports University of Jyväskylä</i> 5, 3 (1978).
P_36	Kaiser-Bunbury	3	240	56	19	1607	0.27	C. N. Kaiser-Bunbury, T. Valentin, J. Mougil, D. Matatiken, J. Ghazoul, <i>J. Ecol.</i> 99, 202 (2011).
P_37	Kaiser-Bunbury	1	210	135	73	3961	0.25	C. N. Kaiser-Bunbury, J. Memmott, C. B. Müller, <i>Perspect. Plant Ecol. Evol. Syst.</i> 11, 241 (2009).
P_38	Kato	1	180	679	91	2392	0.38	M. Kato, T. Makutani, T. Inoue, T. Itino, <i>Contribution from the Biological Laboratory, Kyoto University</i> 27, 309 (1990).
P_39	Kevan	1	73	114	30	2523	0.45	P. G. Kevan, thesis, University of Alberta, Canada (1970).
P_40	Koeniger	1	60	4	35	142	0.15	N. Koeniger, G. Vorwohl, <i>J. Apic. Res.</i> 18, 95 (1979).
P_41	Memmott	1	30	79	25	2183	0.21	J. Memmott, <i>Ecol. Lett.</i> 2, 276 (1999).
P_42	Mosquin	1	13	18	11	134	0.36	T. Mosquin, J. E. H. Martin, <i>Can. Field-Nat.</i> 81, 201 (1967).
P_43	Motten	1	60	44	13	2225	0.40	A. F. Motten, <i>Ecol. Monogr.</i> 56, 21 (1986).
P_44	Ollerton	1	63	56	9	594	0.37	J. Ollerton, S. D. Johnson, L. Cranmer, S. Kellie, <i>Ann. Bot.</i> 92, 807 (2003).
P_45	Poursin	1	90	11	12	321	0.45	J. M. Poursin, <i>Apidologie</i> 13, 227 (1982).
P_46	Queiroz	1	365	8	12	205	0.42	V. Q. Piacentini, I. G. Varassin, <i>J. Trop. Ecol.</i> 23, 663 (2007).
P_47	Reader	1	120	14	4	596	0.38	R. J. Reader, <i>Can. J. Bot.</i> 53, 1300 (1975).
P_48	Schemske	1	90	32	7	299	0.26	D. W. Schemske <i>et al.</i> , <i>Ecology</i> 59, 351 (1978).
P_49	Small	1	60	34	13	992	0.49	E. Small, <i>Can. Field-Nat.</i> 90, 22 (1976).
P_50	Ssymank	1	120	52	44	382	0.39	A. Ssymank, <i>Valucella</i> 6, 81 (2002).
P_51	Ssymank	1	180	75	88	4837	0.44	A. Ssymank, <i>Schriftenreihe für Landschaftspflege und Naturschutz</i> 64, 1 (2001).
P_52	Stiles	1	365	9	9	1026	0.22	F. G. Stiles, <i>Ecology</i> 56, 285 (1975).
P_53	Varassin	1	365	14	20	140	0.13	I. G. Varassin, M. Sazima, <i>Bol. Mus. Biol. Mello Leitão Nova Sér.</i> 11/12, 57 (2000).
P_54	Vazquez	8	150	29	9	662	0.67	D. P. Vázquez, D. Simberloff, <i>Am. Nat.</i> 159, 606 (2002).
P_55	Watts	1	15	8	7	501	0.22	S. Watts, thesis, University of Northampton, UK (2008).
P_56	Watts	9	1	37	23	176	0.25	S. Watts, thesis, University of Northampton, UK (2008).
P_57	Williams	5	180	69	34	399	0.38	N. M. Williams, D. Cariveau, R. Winfree, C. Kremen, <i>Basic Appl. Ecol.</i> 12, 332 (2011).
P_58	Williams	1	15	17	9	186	0.52	N. H. Williams, C. H. Dodson, <i>Evolution</i> 26, 84 (1972).

**Table S1** (continued)

Region_ID	Data holder	Network type	Latitude	Longitude	Country	Altitude	Glaciation LGM	Habitat	Completeness	Focus	Design
S_1	Baird	seed dispersal	40.3	-74.7	USA	20	no	forest	full	plant	representative
S_2	Beehler	seed dispersal	-7.3	146.7	P. New Guinea	1430	no	forest	restricted	plant	standardized
S_3	Carlo	seed dispersal	18.3	-66.6	Puerto Rico	408	no	forest	full	animal	representative
S_4	Dehling	seed dispersal	-13.1	-71.6	Peru	2200	no	forest	full	plant	representative
S_5	Engel	seed dispersal	-4.2	39.4	Kenya	190	no	forest	full	animal	representative
S_6	Faria/Galetti	seed dispersal	-22.8	-47.1	Brasil	650	no	forest	full	animal/plant	representative
S_7	Frost	seed dispersal	-29.0	31.8	South Africa	20	no	forest	full	plant	representative
S_8	Gorchov	seed dispersal	-4.9	-73.8	Peru	120	no	forest	full	animal	representative
S_9	Hovestadt	seed dispersal	9.0	-3.6	Ivory Coast	240	no	non-forest	full	plant	representative
S_10	Jordano	seed dispersal	37.6	-2.5	Spain	1615	no	forest	full	plant	representative
S_11	Kantak	seed dispersal	18.5	-89.5	Mexico	280	no	forest	full	plant	standardized
S_12	Passos	seed dispersal	-24.3	-48.4	Brasil	615	no	forest	restricted	animal	representative
S_13	Pedro	seed dispersal	-19.2	-48.4	Brasil	800	no	forest	restricted	animal	representative
S_14	Poulin	seed dispersal	9.2	-79.7	Panama	150	no	forest	full	animal	representative
S_15	Schleuning	seed dispersal	50.3	8.7	Germany	208	no	non-forest	full	plant	representative
S_16	Schleuning	seed dispersal	0.4	34.9	Kenya	1600	no	forest	full	plant	standardized
S_17	Silveira	seed dispersal	-22.4	-47.0	Brasil	610	no	forest	restricted	animal	representative
S_18	Snow	seed dispersal	51.8	-0.8	UK	100	no	non-forest	restricted	plant	representative
S_19	Snow	seed dispersal	10.7	-61.2	Trinidad	550	no	forest	full	plant	representative
S_20	Sorensen	seed dispersal	51.8	-1.3	UK	120	no	forest	full	plant	representative
S_21	Stiebel	seed dispersal	51.2	9.0	Germany	300	no	forest	full	plant	representative
S_22	Stiles/Lopez	seed dispersal	10.4	-84.0	Costa Rica	50	no	forest	restricted	plant	representative

**Table S1** (continued)

Region_ID	Data holder	# networks	mean duration [days]	mean # animals	mean # plants	mean # interactions	$\Delta H_2$ '	Further information
S_1	Baird	1	180	21	7	655	0.44	J. W. Baird, <i>Wilson Bull.</i> <b>92</b> , 63 (1980).
S_2	Beehler	1	249	9	31	1189	0.23	B. Beehler, <i>Auk</i> <b>100</b> , 1 (1983).
S_3	Carlo	4	48	16	26	237	0.27	T. A. Carlo, J. A. Collazo, M. J. Groom, <i>Oecologia</i> <b>134</b> , 119 (2003).
S_4	Dehling	2	16	47	34	924	0.29	Data collected by D.M. Dehling (coauthor) between December 2009 and February 2010 in the Manú Biosphere Reserve, Peru.
S_5	Engel	1	365	33	219	3730	0.35	T. R. Engel, thesis, University of Bayreuth, Germany (2000).
S_6	Faria/Galetti	2	365	19	26	272	0.23	D. M. Faria, thesis, Universidade Estadual de Campinas, São Paulo, Brazil (1996); M. Galetti, M. A. Pizo, <i>Ararajuba</i> <b>4</b> , 71 (1996).
S_7	Frost	1	365	10	16	3554	0.24	P. G. H. Frost, in <i>Acta XVII Congressus Internationalis Ornithologici</i> , R. Noring, Ed. (Berlin, 1980), pp. 1179-1184.
S_8	Gorchov	1	365	18	91	1186	0.34	D. L. Gorchov, F. Cornejo, C. F. Ascorra, M. Jaramillo, <i>Oikos</i> <b>74</b> , 235 (1995).
S_9	Hovestadt	1	365	48	34	17575	0.17	T. Hovestadt, thesis, University of Würzburg, Germany (1997).
S_10	Jordano	1	365	33	25	7010	0.34	P. Jordano, <i>Ardeola</i> <b>32</b> , 69 (1985).
S_11	Kantak	1	80	27	5	5549	0.31	G. E. Kantak, <i>Auk</i> <b>96</b> , 183 (1979).
S_12	Passos	1	365	6	23	101	0.25	F. C. Passos, W. R. Silva, W. A. Pedro, M. R. Bonin, <i>Rev. Bras. Zool.</i> <b>20</b> , 511 (2003).
S_13	Pedro	1	365	7	13	108	0.35	W. A. Pedro, thesis, Universidade de Campinas, Campinas, Brazil (1992).
S_14	Poulin	1	84	20	17	492	0.15	B. Poulin, S. J. Wright, G. Lefebvre, O. Calderón, <i>J. Trop. Ecol.</i> <b>15</b> , 213.
S_15	Schleuning	8	60	15	10	223	0.48	M. Plein, thesis, University of Mainz, Germany (2011).
S_16	Schleuning	1	90	88	33	3447	0.25	M. Schleuning <i>et al.</i> , <i>Ecology</i> <b>92</b> , 26 (2011).
S_17	Silveira	1	365	6	7	182	0.13	M. Silveira, thesis, Universidade Estadual de São Paulo, Rio Claro, Brazil (2006).
S_18	Snow	1	300	19	29	19946	0.30	B. K. Snow, D. W. Snow, <i>Birds and Berries</i> (T & AD Poyser, Calton, England, 1988).
S_19	Snow	1	60	14	50	2144	0.25	B. K. Snow, D. W. Snow, <i>J. Anim. Ecol.</i> <b>41</b> , 471 (1972).
S_20	Sorensen	1	220	14	11	7434	0.46	A. E. Sorensen, <i>Oecologia</i> <b>50</b> , 242 (1981).
S_21	Stiebel	1	365	30	29	6360	0.39	H. Stiebel, F. Bairlein, <i>Vogelwarte</i> <b>46</b> , 1 (2008).
S_22	Stiles/Lopez	2	303	21	22	798	0.20	F. G. Stiles, <i>Brenesia</i> <b>15</b> , 151 (1979); J. E. Lopez, C. Vaughan, <i>Revista de Biología Tropical</i> <b>55</b> , 301 (2007).



**Table S2, Related to Figure 2. Minimal Adequate Linear Models of the Effects of Multiple Predictor Variables on Network Specialization ( $\Delta H_2'$ ) in 80 Study Regions**

(A) All minimal adequate linear models with  $\Delta AICc < 2$

Predictor	$\beta$	t	p
Best model, $R = 0.32$ , $p < 0.001$			
Network type (pollination)	0.058	2.46	0.016
Growing degree days	-0.594	-5.29	< 0.001
Habitat type (forest)	0.065	2.47	0.016
Alternative model, $\Delta AICc = 0.94$ , $R = 0.34$ , $p < 0.001$			
Network type (pollination)	0.068	2.71	0.008
Growing degree days	-0.563	-4.89	< 0.001
Habitat type (forest)	0.071	2.65	0.010
Taxonomic focus (full)	0.028	1.15	0.253
Alternative model, $\Delta AICc = 1.62$ , $R = 0.35$ , $p < 0.001$			
Network type (pollination)	0.127	2.66	0.010
Growing degree days	-0.552	-4.74	< 0.001
Habitat type (forest)	0.067	2.50	0.015
Climate-change velocity	0.331	1.69	0.096
Network type x Climate-change velocity	-0.351	-1.60	0.113
Alternative model, $\Delta AICc = 1.63$ , $R = 0.33$ , $p < 0.001$			
Network type (pollination)	0.052	2.09	0.040
Growing degree days	-0.572	-4.96	< 0.001
Habitat type (forest)	0.068	2.56	0.013
Observation time span	-0.087	-0.82	0.418

Predictors were past climate stability (glaciation during LGM, climate-change velocity), contemporary climate (growing degree days), and potential confounding factors (time span of observation, habitat type, taxonomic sampling focus); network type (pollination, seed dispersal) was included in all models. Based on the results of univariate models, we included the interaction term between climate-change velocity and network type (pollination, seed dispersal) in all models with climate-change velocity.

(B) Akaike weights for all predictor variables across all 63 model combinations.

Predictor variable	Akaike weight
Growing degree days	0.999
Habitat type	0.898
Taxonomic focus	0.343
Climate-change velocity	0.323
Sampling period	0.308
Glaciated during LGM	0.245

We fitted linear models for all combinations of predictor variables (n = 63 models) and calculated the Akaike weights for each fitted model. The Akaike weight gives the likelihood that a model is the best available model, and thus the summed Akaike weight for each predictor variable measures the relative importance of each variable in contributing to the best model. Note that none of the potentially confounding variables (habitat type, taxonomic focus, sampling period) significantly affected  $\Delta H_2'$  in univariate models ( $p > 0.05$  in all cases).

**Table S3, Related to Table 1. Correlations between Different Specialization Metrics and Sampling Effort and Network Size**

	(A) Sampling effort		(B) Network size	
	r	p	r	p
Specialization $\Delta H_2'$	-0.015	0.898	0.075	0.507
Specialization $H_2'$	<b>-0.361</b>	<b>0.001</b>	0.093	0.413
Connectance	0.027	0.810	<b>-0.700</b>	<b>&lt;0.001</b>
Unweighted Generality	<b>0.446</b>	<b>&lt;0.001</b>	0.088	0.438
Weighted Generality	<b>0.313</b>	<b>0.005</b>	0.076	0.501
Plant specialization $d_i'$	<b>-0.237</b>	<b>0.035</b>	<b>0.320</b>	<b>0.004</b>
Animal specialization $d_j'$	<b>-0.268</b>	<b>0.017</b>	0.167	0.138

(A) Sampling effort is estimated by the number of observed interactions events (log10-scale), and (B) network size equals the sum of plant and animal species in a network (log10-scale). Pearson correlation coefficients r and p-values are given; significant correlations are printed bold. Pearson correlations r were calculated with region as the unit of replication (n = 80 in all cases).  $\Delta H_2'$  is the only index that is neither related to sampling effort nor to network size and was therefore the preferred metric in the main manuscript.

## 2. Supplemental Experimental Procedures

### Data Set Description

We compiled a dataset of quantitative interaction networks between plants and their animal pollinators or seed dispersers from original sources, accessible databases [41, 42] and co-authors. Each network matrix in the dataset describes the community-wide pattern of interactions among plants and flower visitors (called ‘pollination networks’) or plants and fruit-eating animals (called ‘seed dispersal networks’). Most networks were recorded by observing consumer visits to plant individuals, either in transect walks or in focal plant observations. Studies based on pollen or fecal samples from consumer species were also included but were less numerous (cf. ‘sampling focus’ in Table S1). Most network studies used representative sampling designs, i.e., distributed observation times per plant species proportional to their abundance, while few studies standardized observation times per species (‘sampling design’ in Table S1). All network studies provided an estimate of the number of interaction events (interaction strength) between a plant and an animal species, e.g., the number of pollinator or seed-disperser individuals observed feeding on a plant species or the number of individuals of a consumer species carrying pollen or seeds of a particular plant species. Estimates of interaction strength are a meaningful surrogate for the mutualistic importance of a consumer species for a plant species and vice versa because interaction frequencies have a stronger effect on mutualist species than interaction efficiencies per visit [12, 43].

We only included networks in our meta-analysis that comprised at least 50 interaction events and more than four plant and four consumer species (i.e., adequately sampled networks), that were limited to a single community, and that were dominated by native plants or animals (threshold: > 80% of interactions from native species). We excluded 71 networks that did not meet these criteria, and the final dataset comprised 282 quantitative networks. For each of these networks, we recorded the location of sampling (latitude, longitude, altitude), the predominant habitat type (forest vs. non-forest habitats), the taxonomic completeness of sampling (entire species community vs. single plant and/or animal family) and the duration of sampling (the maximum duration was defined to be an entire year, i.e., 365 days).

The number of networks strongly varied among the original studies. To avoid over-representation of particular studies in the analysis, we assigned each network to a sampling region. These regions were defined by the original studies that focused on a particular type of habitat in a given area. However, networks from the same study that were more than 100 km apart were assigned to distinct regions; this criterion applied to four of the original studies. Moreover, different studies that were conducted at the same location were assigned to belong to the same sampling region; this was the case for two regions: La Selva (Costa Rica) and Santa Genebra Reserve (Brazil).

### Author Contributions

The project was developed by MS, JF, AMK, DMD, RJM, CFD and NB. Network data were collected and provided by MS, JF, SA, RA, MA, GKSA, SB, KBG, RB, BD, DMD, AG, MH, AH, CNKB, TT, SW, CNW, MW, NMW, CW, CFD and NB. Climate and plant-richness variables were compiled by DMD, TH, HK, BS, WJS and JCS. Analyses and presentation of results were conducted by MS, JF, CFD and NB. All co-authors contributed to the interpretation of the results. The manuscript was written by MS and JF in collaboration with all co-authors.

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### **3. Supplemental References**

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