Ecosystem size and complexity dictate riverine biodiversity
Supplementary Information for:

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Contents

Fish community data

Hokkaido, Japan

We used data from the Hokkaido Freshwater Fish Database HFish[1], monitoring data at protected watersheds[2,3], and primary data collected from literature[4], which collectively cover the entire Hokkaido island. Data were collected from summer to fall. We screened data through the following procedure:

1. We listed recorded fish species and re-organized species names to be consistent across the data sets.

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2. We selected sampling sites based on the following criteria: (1) surveys were conducted with netting and/or electrofishing, (2) surveys were designed to collect a whole fish community, (3) sites contained reliable coordinates (sites with coordinates identical at 3 decimal degrees were treated as the same site), and (4) sites did not involve unidentified species that are rarely observed in the data set (< 100 sites occurrence).
3. For sites with multiple visits (i.e., temporal replicates), we used the latest-year observation at each sampling site to minimize variation in sampling efforts among sites. Surveys that occurred in the same year were aggregated into a single observation.
4. We confined sites to those with the latest observation year of ≥ 1990. Although the data set contained observations from 1953, we added this restriction to align the observation period with the data set in the Midwest, US.
5. Four genera (Lethenteron, Pungitius, Rhinogobius, and Tribolodon) were treated as species groups (i.e., spp.) as taxonomic resolutions varied greatly among data sources.

Midwest, US

We assembled fish community data collected by the Iowa Department of Natural Resources, Illinois Environmental Protection Agency and Illinois Department of Natural Resources, Minnesota Pollution Control Agency, and Wisconsin Department of Natural Resources. These data sets cover most of Upper Mississippi (HUC 2, region 07) and the part of Great Lakes (HUC 2, region 04), Missouri (HUC 2, region 10), and Ohio (HUC 2, region 05). Data were collected from summer to fall with electrofishing (backpack, barge-type, or boat-mounted) and supplemental netting at some locations. We screened data through the following procedure:

1. We used data of the Upper Mississippi (HUC 2, region 07) and Great Lakes basins (HUC 2, region 04) as most sites are included in these regions.
2. We removed records of unidentified species, hybrid species, and commercial species that are apparently absent in the wild (e.g., goldfish).
3. We used the latest observation at each sampling site to minimize variation in sampling efforts among sites.

Tables

Table S1 Species list in Hokkaido, Japan

Species list in Hokkaido, Japan. Species are ordered alphabetically.

Species	Number of sites present
Acanthogobius lactipes	87
Anguilla japonica	1
Carassius buergeri subsp. 2	5
Carassius cuvieri	32
Carassius sp.	240
Channa argus	3
Cottus amblystomopsis	65
Cottus hangiongensis	161
Cottus nozawae	918
Cottus sp. ME	25
Cyprinus carpio	56
Gasterosteus aculeatus	228
Gnathopogon caerulescens	1
Gnathopogon elongatus elongatus	7
Gymnogobius breunigii	56
Gymnogobius castaneus complex	178
Gymnogobius opperiens	122
Gymnogobius petschiliensis	2
Gymnogobius urotaenia	433
Hucho perryi	63
Hypomesus nipponensis	228
Hypomesus olidus	12
Lefua nikkonis	24
Lethenteron spp.	863
Leucopsarion petersii	4
Luciogobius guttatus	17
Misgurnus anguillicaudatus	245
Noemacheilus barbatulus	1750
Oncorhynchus gorbuscha	43
Oncorhynchus keta	211
Oncorhynchus masou masou	1667
Oncorhynchus mykiss	489
Oncorhynchus nerka	6
Opsariichthys platypus	1
Osmerus dentex	13
Phoxinus percnurus sachalinensis	80
Plecoglossus altivelis altivelis	157
Pseudorasbora parva	104
Pungitius spp.	347
Rhinogobius spp.	244
Rhodeus ocellatus ocellatus	32
Salangichthys microdon	20
Salmo trutta	15
Salvelinus fontinalis	2
Salvelinus leucomaenis leucomaenis	790
Salvelinus malma	282
Salvelinus malma miyabei	2

Species	Number of sites present
Silurus asotus	7
Spirinchus lanceolatus	10
Tribolodon spp.	1410
Tridentiger brevispinis	155
Tridentiger obscurus	8

Figures

Figure S1 Influence of ecosystem size ($p_d = 0.1$, $\sigma_h = 1$, $\sigma_l = 0.01$)

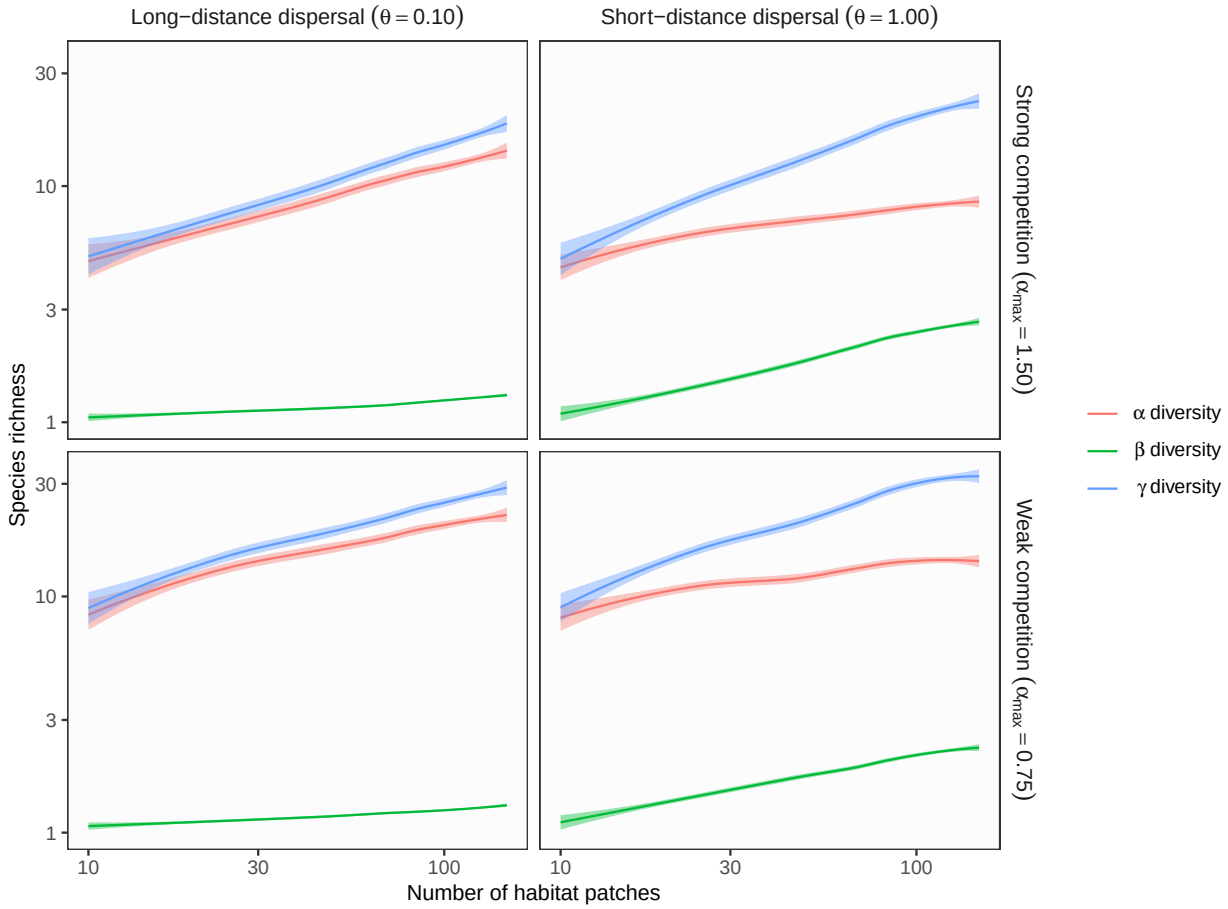

Figure S1 Theoretical predictions for ecosystem size influences (the number of habitat patches) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) exceeds local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.1$; environmental variation at headwaters $\sigma_h = 1$; local environmental noise $\sigma_l = 0.01$.

Figure S2 Influence of ecosystem size ($p_d = 0.1$, $\sigma_h = 1$, $\sigma_l = 1$)

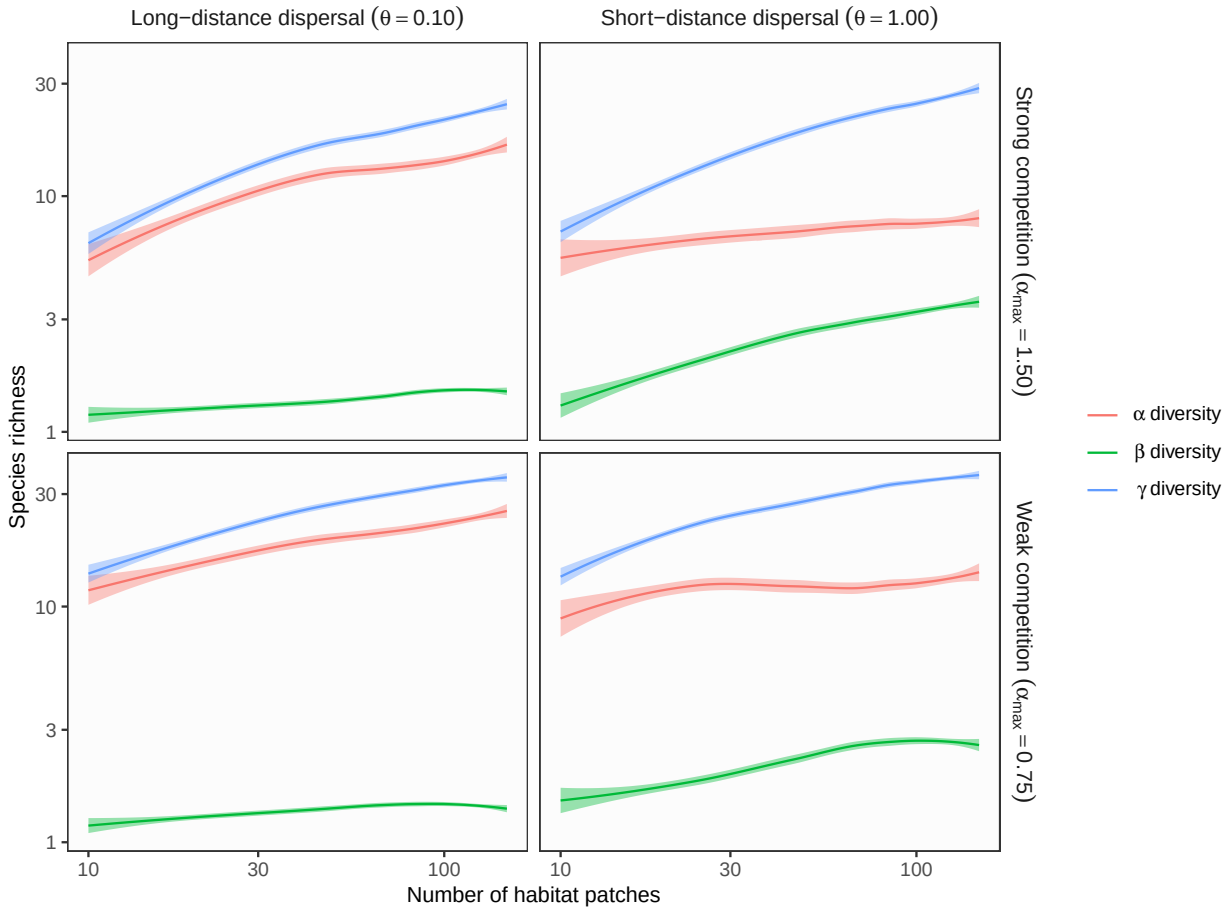

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Figure S3 Influence of ecosystem size ($p_d = 0.1$, $\sigma_h = 0.01$, $\sigma_l = 0.01$)

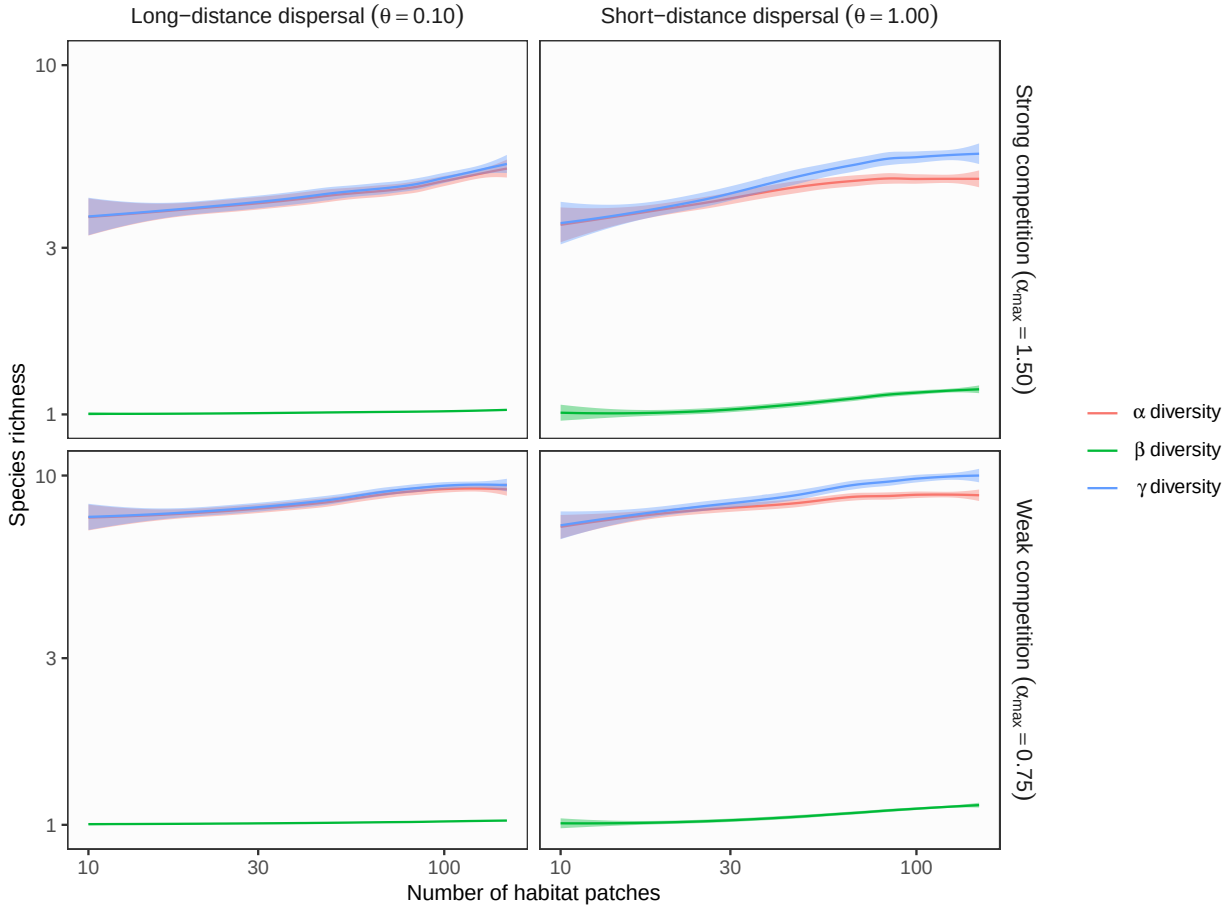

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Figure S4 Influence of ecosystem size ($p_d = 0.1$, $\sigma_h = 0.01$, $\sigma_l = 1$)

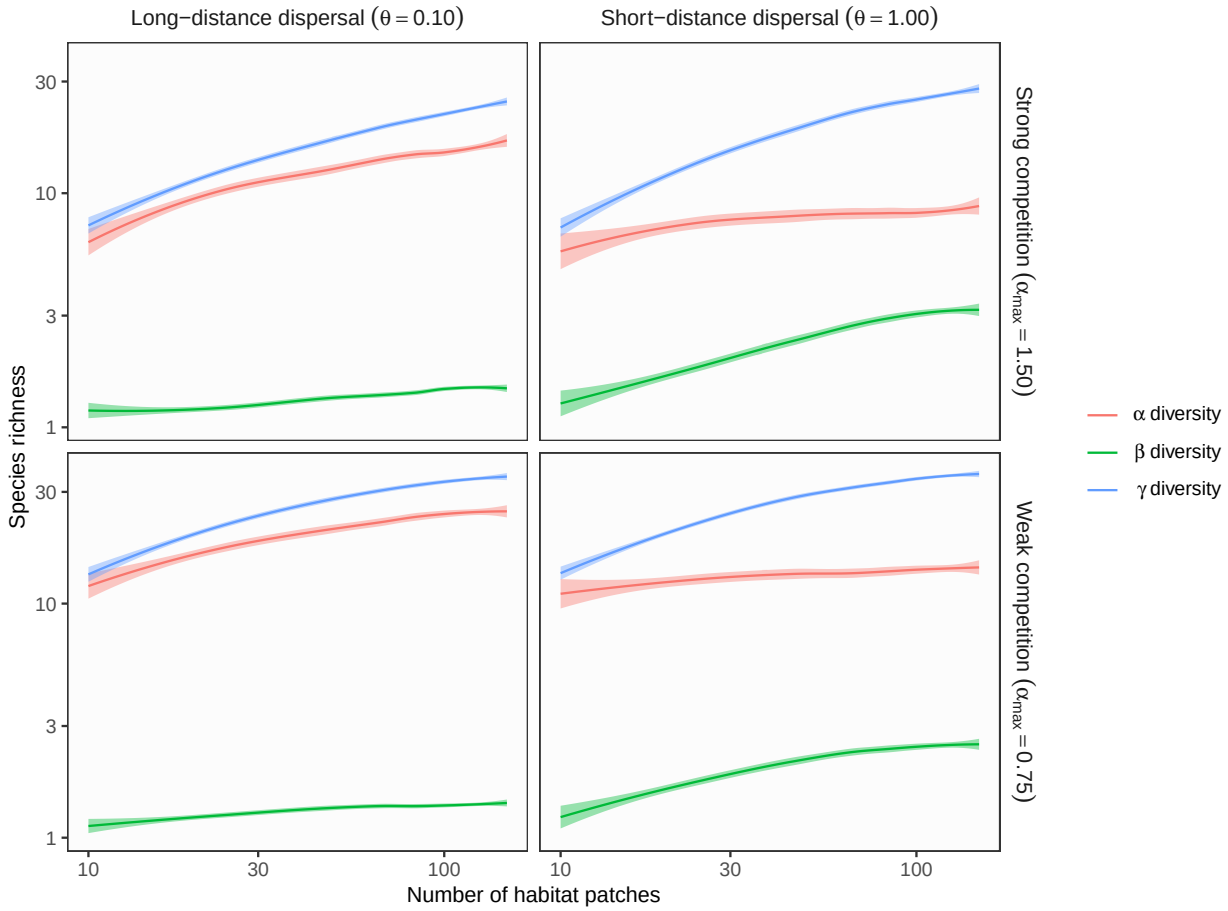

Figure S4 Theoretical predictions for ecosystem size influences (the number of habitat patches) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) is less than local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.1$; environmental variation at headwaters $\sigma_h = 0.01$; local environmental noise $\sigma_l = 1$.

Figure S5 Influence of ecosystem size ($p_d = 0.01$, $\sigma_h = 1$, $\sigma_l = 1$)

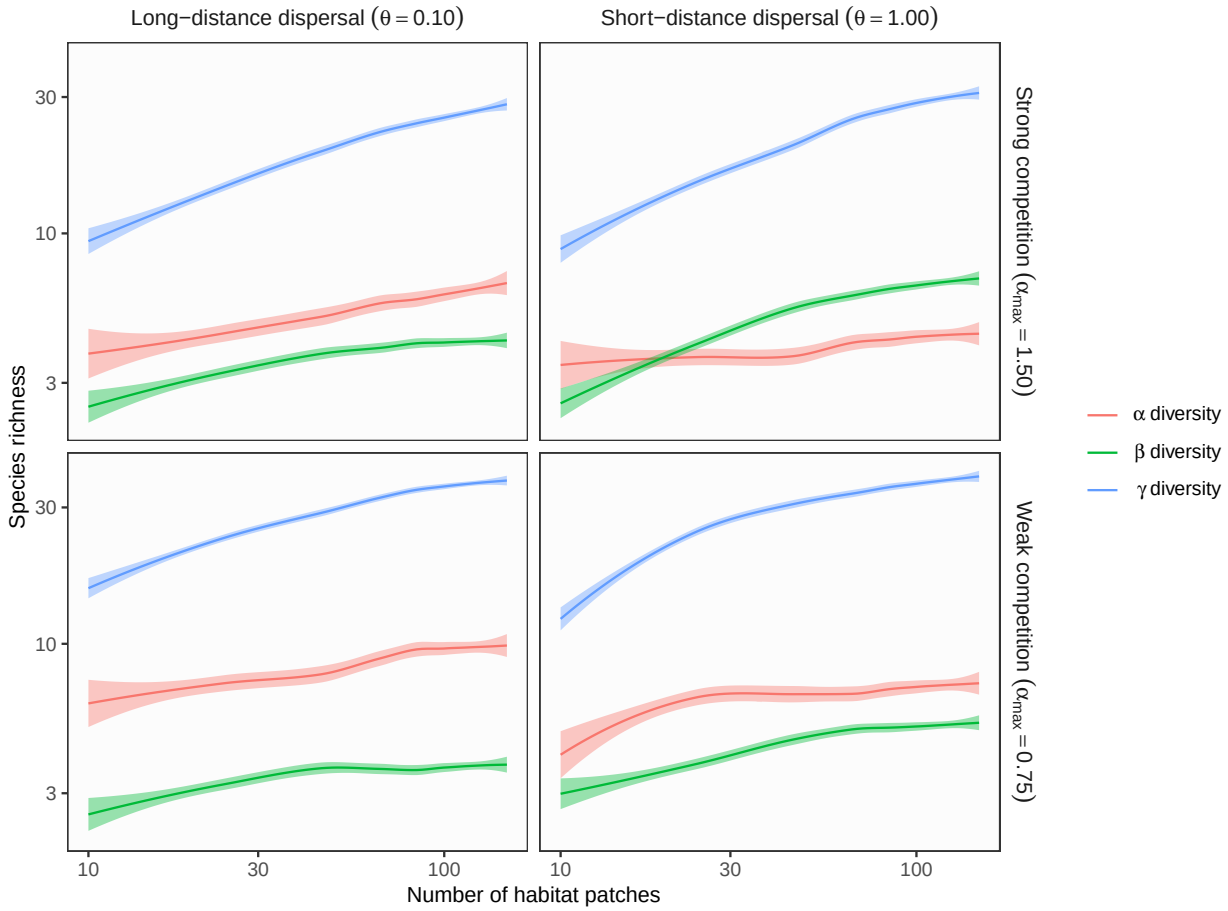

Figure S5 Theoretical predictions for ecosystem size influences (the number of habitat patches) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) is equal to local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.01$; environmental variation at headwaters $\sigma_h = 1$; local environmental noise $\sigma_l = 1$.

Figure S6 Influence of ecosystem size ($p_d = 0.01$, $\sigma_h = 0.01$, $\sigma_l = 0.01$)

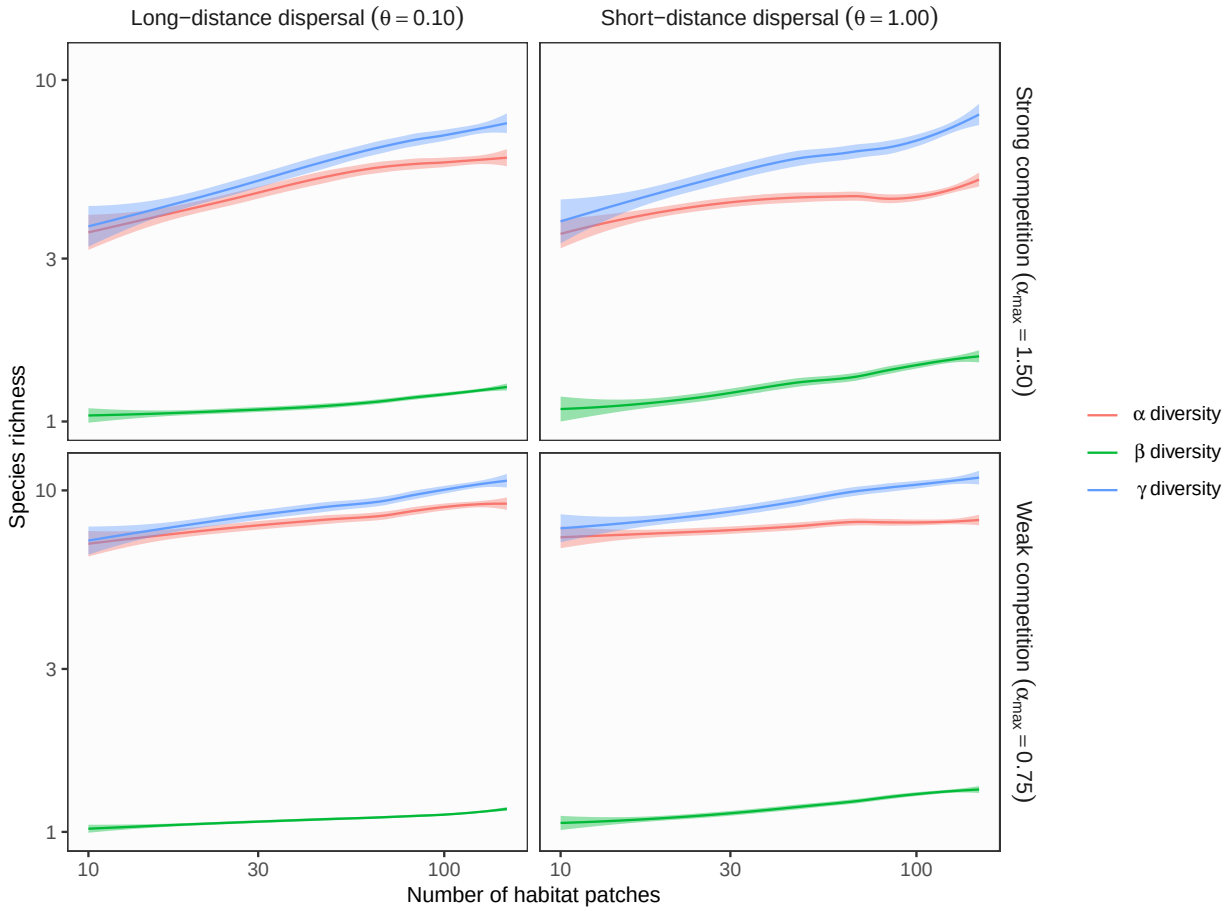

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Figure S7 Influence of ecosystem size ($p_d = 0.01$, $\sigma_h = 0.01$, $\sigma_l = 1$)

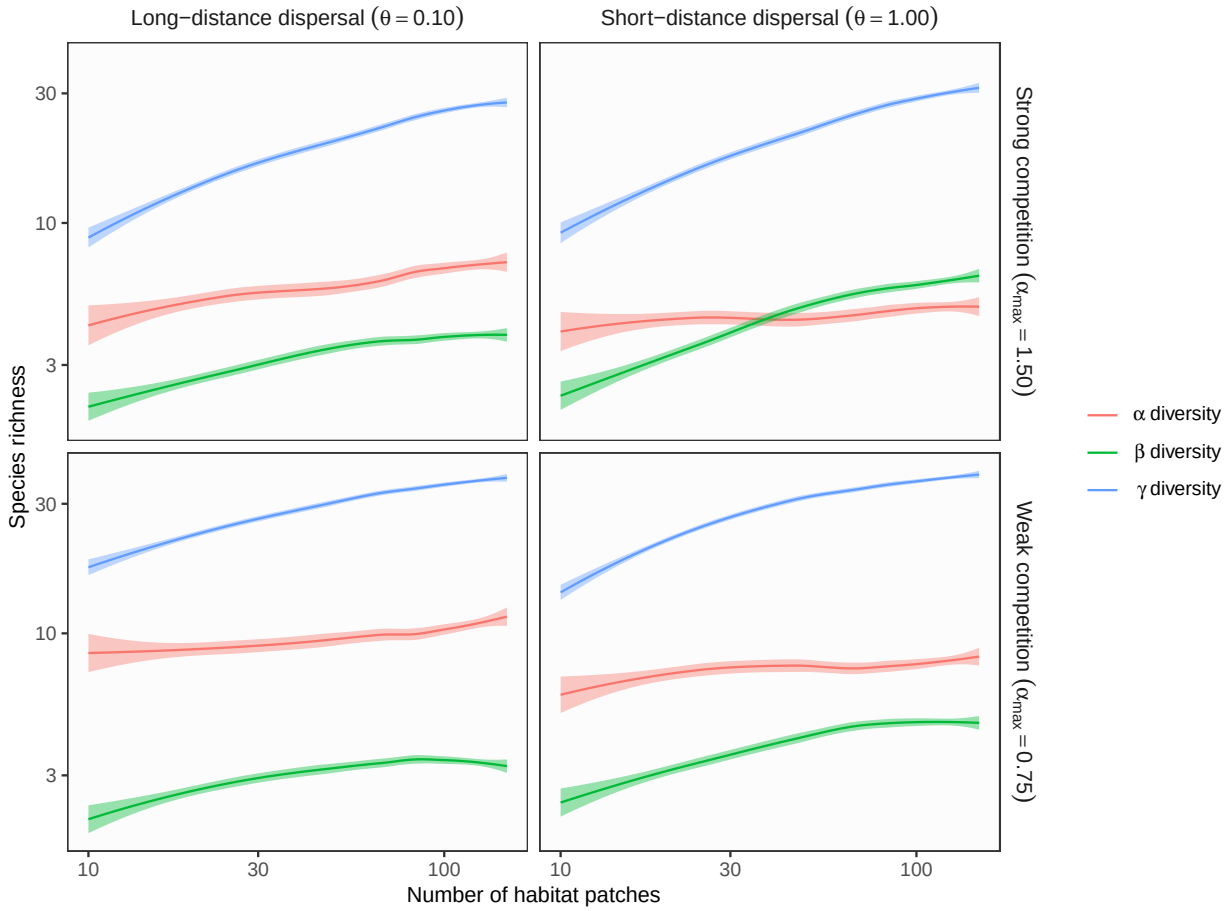

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Figure S8 Influence of ecosystem complexity ($p_d = 0.1$, $\sigma_h = 1$, $\sigma_l = 0.01$)

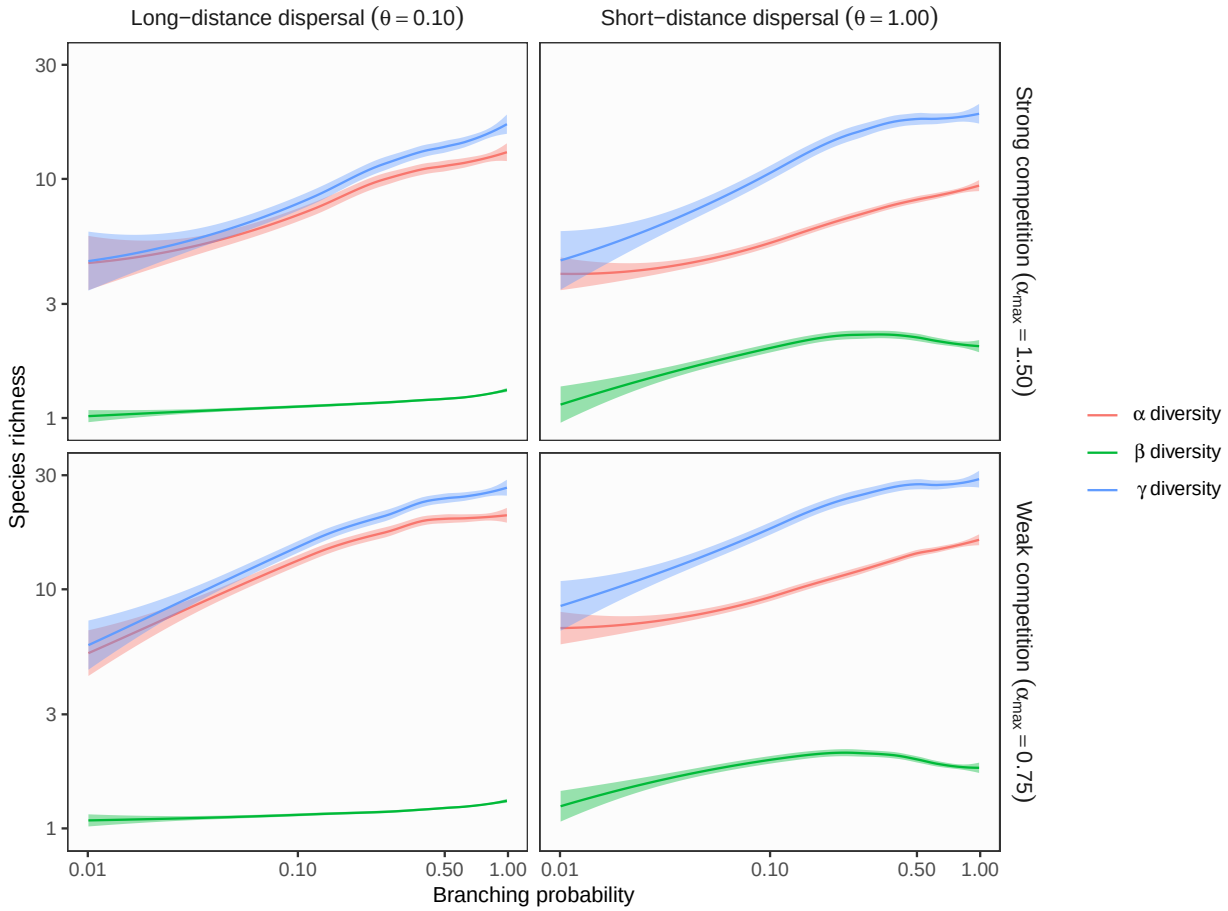

Figure S8 Theoretical predictions for ecosystem complexity influences (branching probability) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) exceeds local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.1$; environmental variation at headwaters $\sigma_h = 1$; local environmental noise $\sigma_l = 0.01$.

Figure S9 Influence of ecosystem complexity ($p_d = 0.1$, $\sigma_h = 1$, $\sigma_l = 1$)

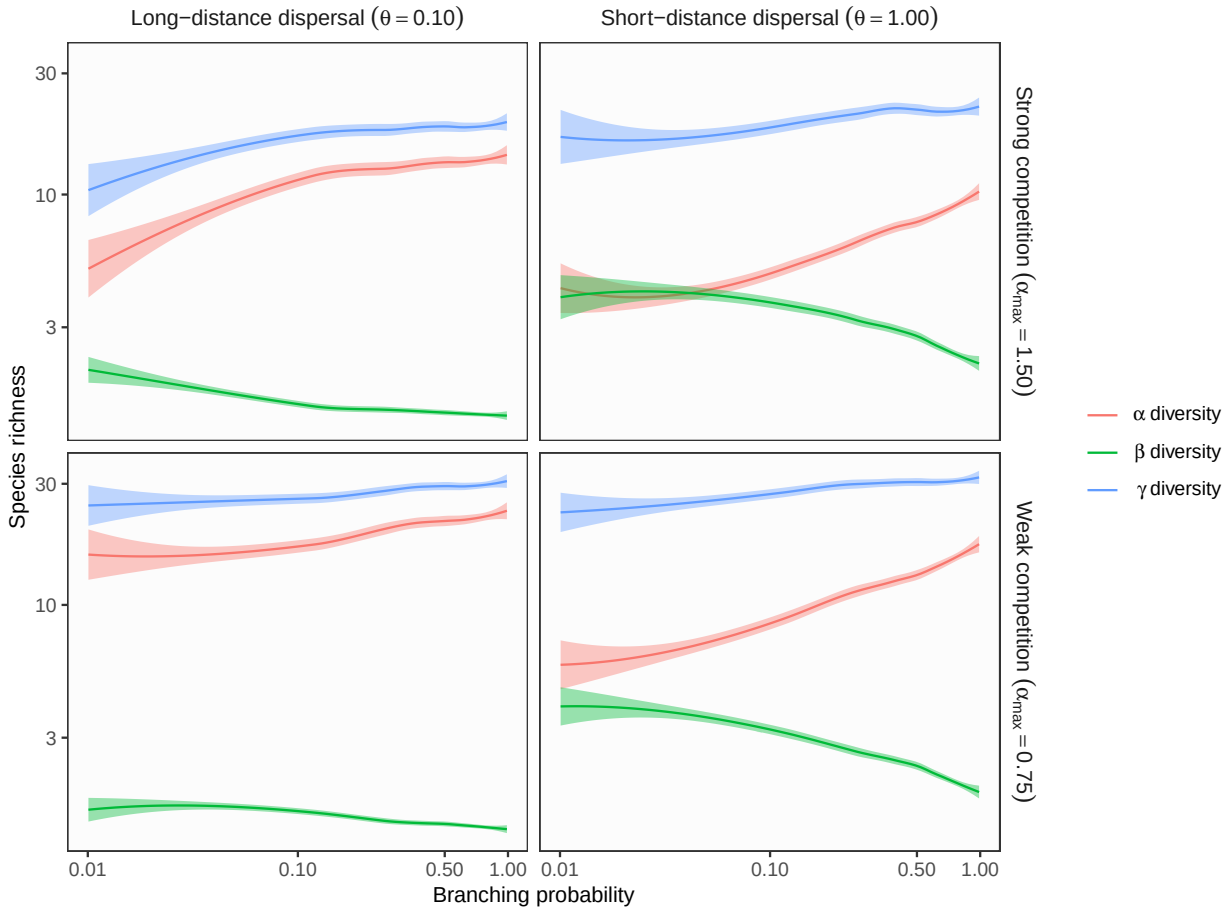

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Figure S10 Influence of ecosystem complexity ($p_d = 0.1$, $\sigma_h = 0.01$, $\sigma_l = 0.01$)

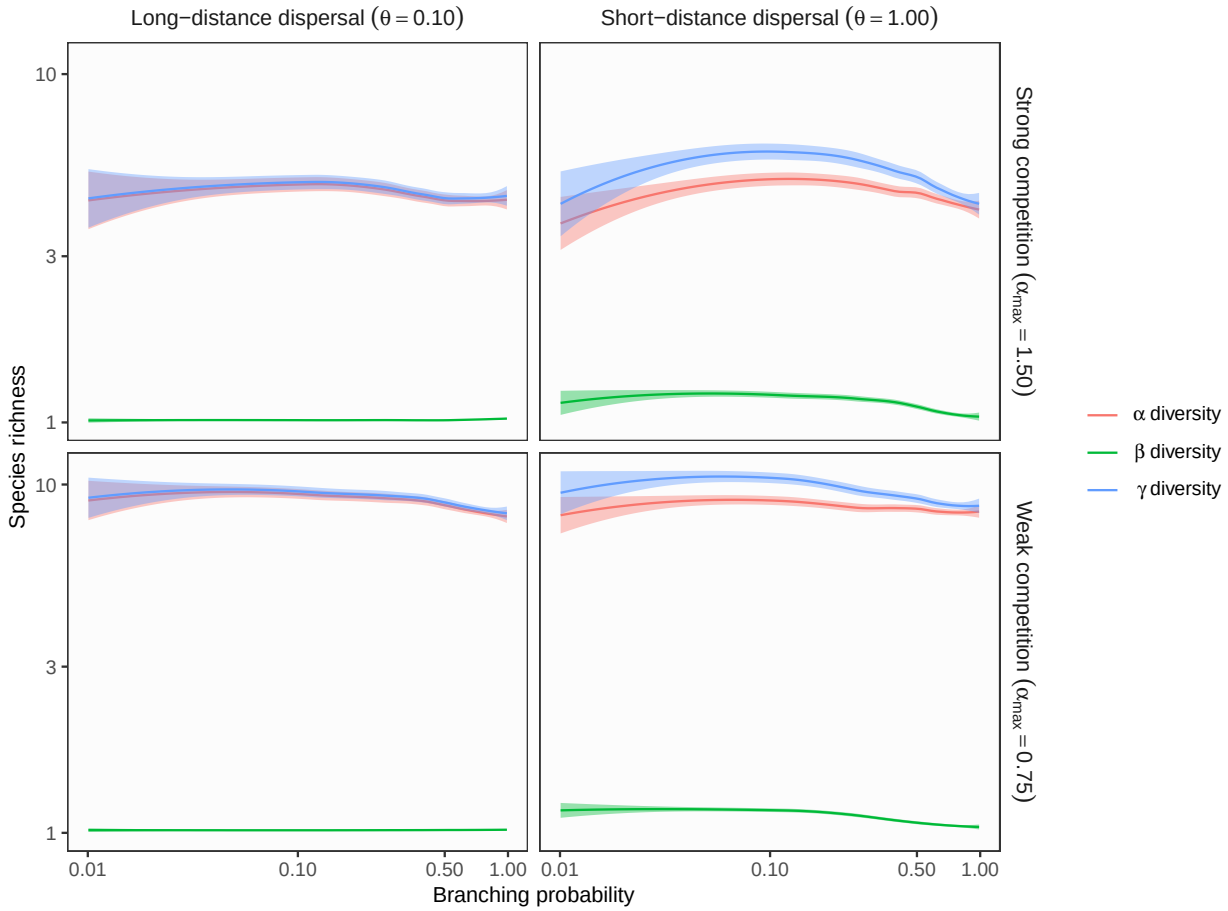

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Figure S11 Influence of ecosystem complexity ($p_d = 0.1$, $\sigma_h = 0.01$, $\sigma_l = 1$)

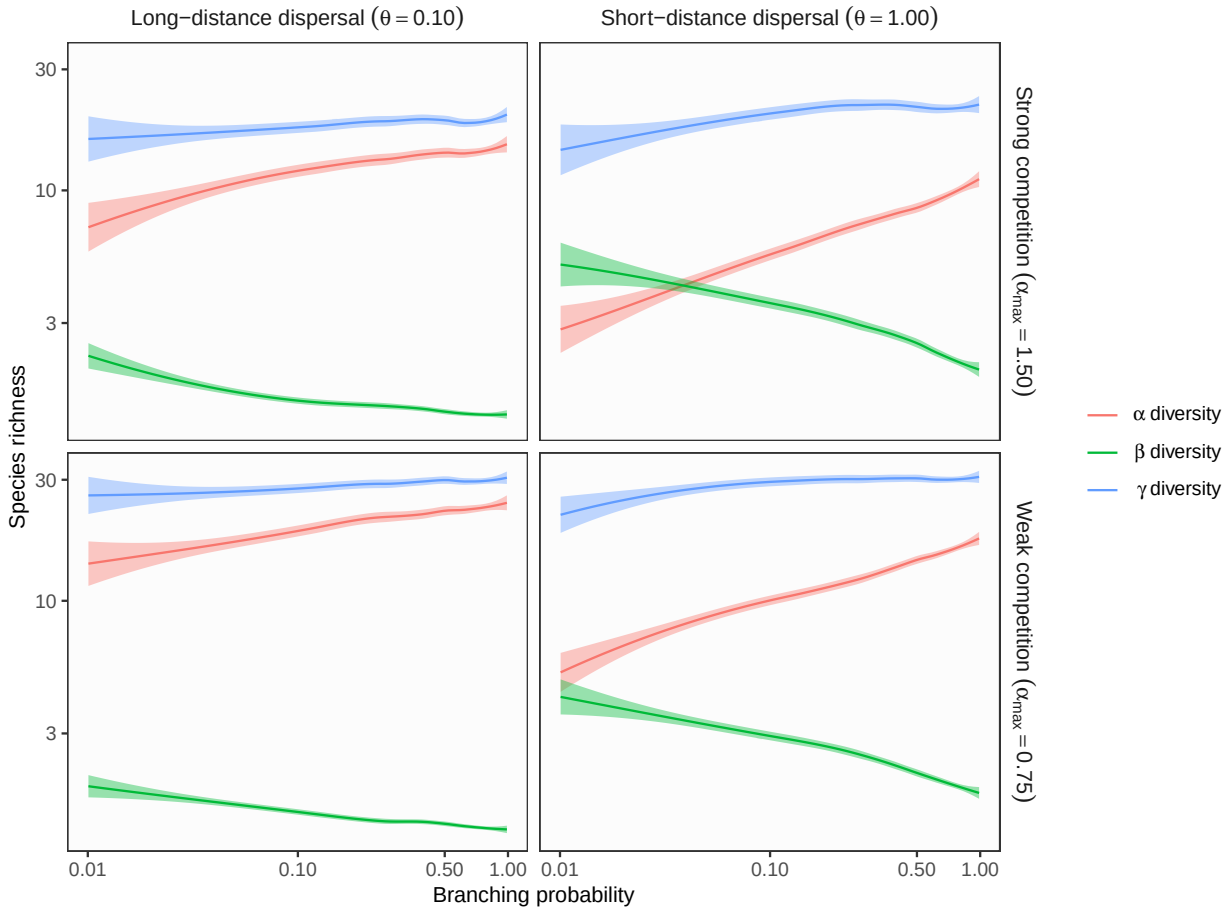

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Figure S12 Influence of ecosystem complexity ($p_d = 0.01$, $\sigma_h = 1$, $\sigma_l = 1$)

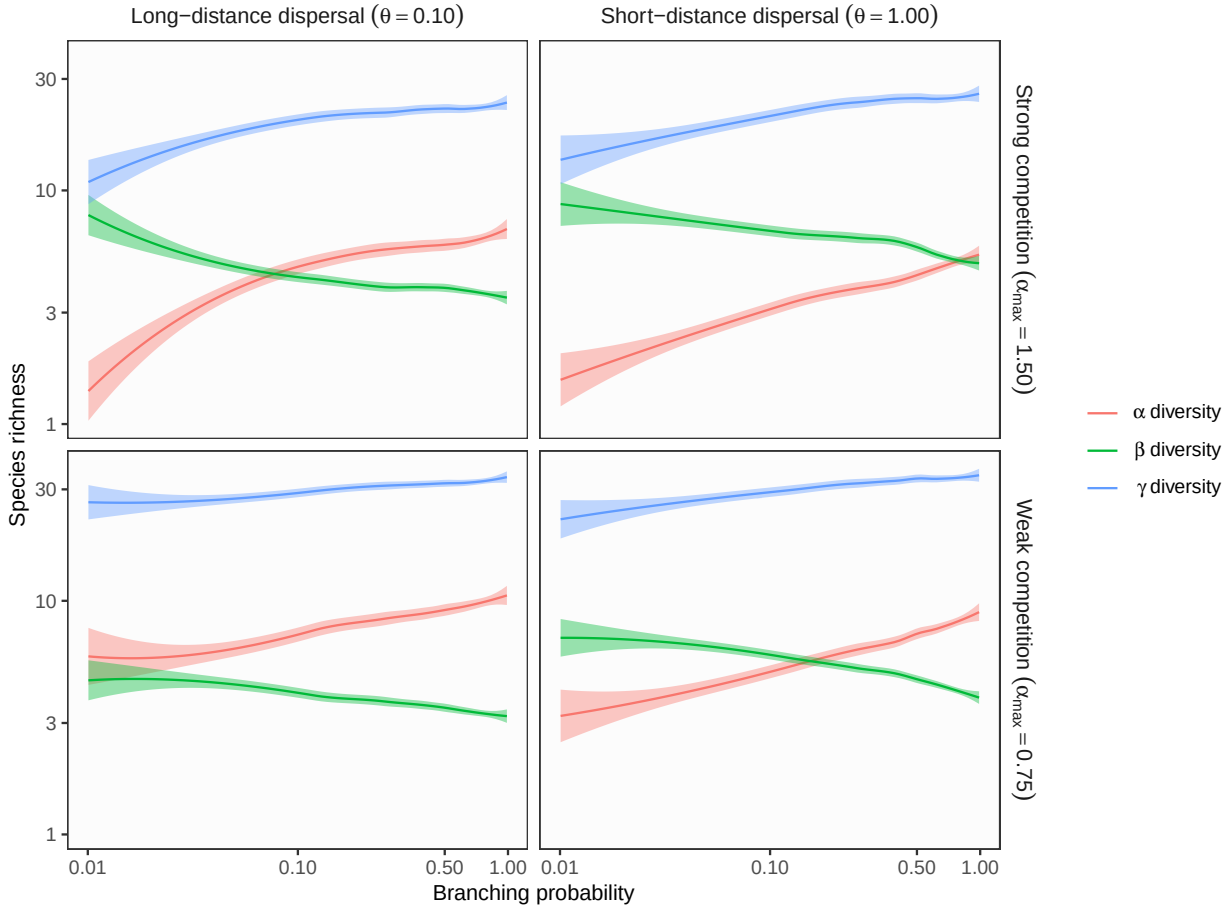

Figure S12 Theoretical predictions for ecosystem complexity influences (branching probability) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) is equal to local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.01$; environmental variation at headwaters $\sigma_h = 1$; local environmental noise $\sigma_l = 1$.

Figure S13 Influence of ecosystem complexity ($p_d = 0.01$, $\sigma_h = 0.01$, $\sigma_l = 0.01$)

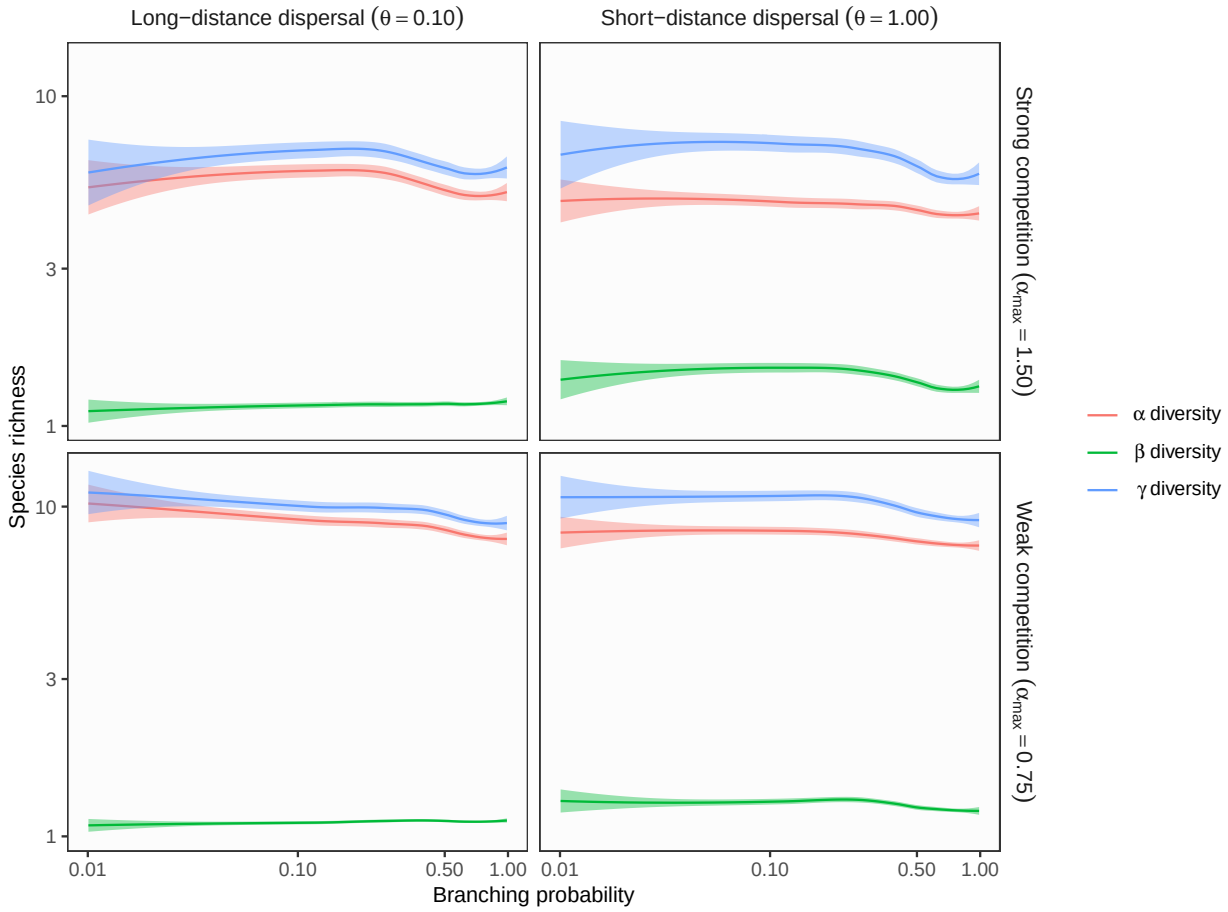

Figure S13 Theoretical predictions for ecosystem complexity influences (branching probability) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) is equal to local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.01$; environmental variation at headwaters $\sigma_h = 0.01$; local environmental noise $\sigma_l = 0.01$.

Figure S14 Influence of ecosystem complexity ($p_d = 0.01$, $\sigma_h = 0.01$, $\sigma_l = 1$)

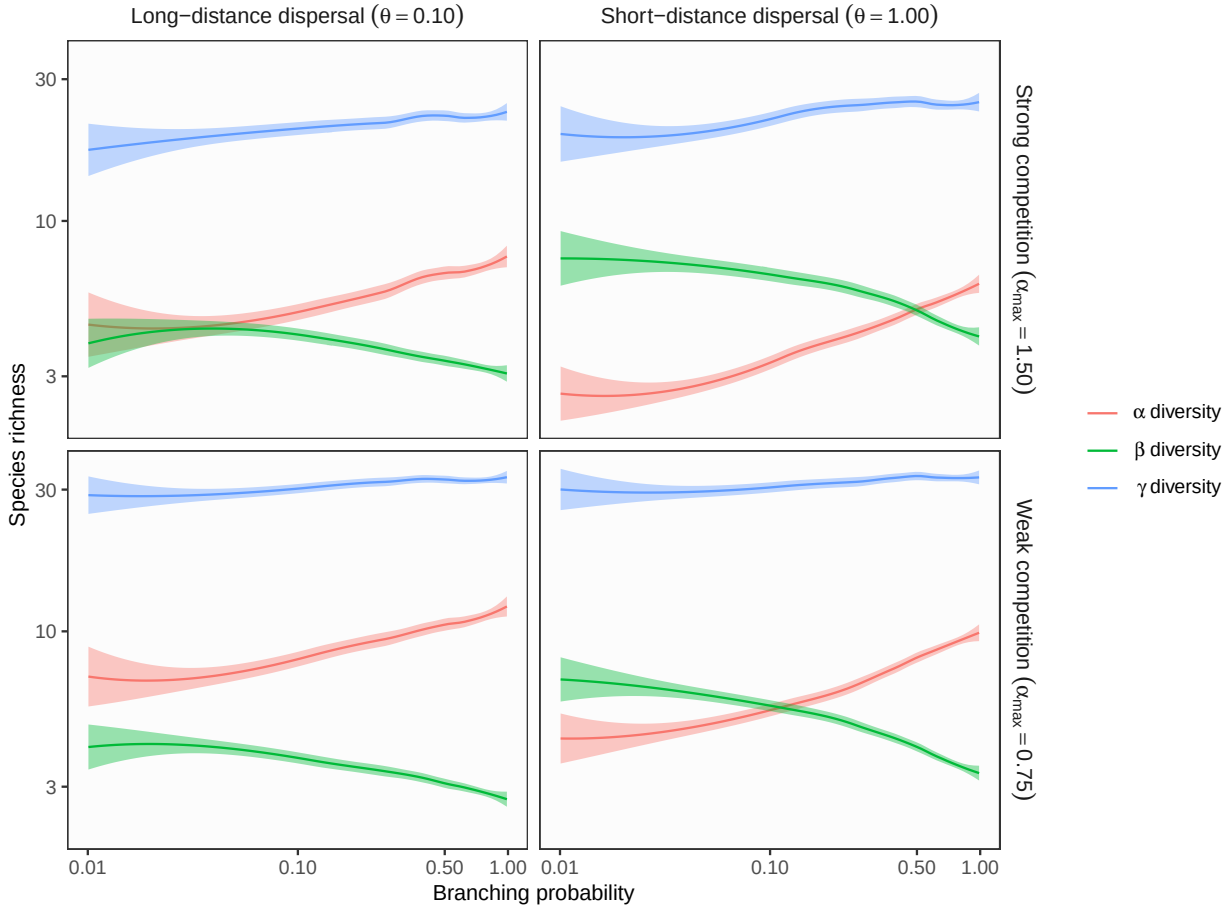

Figure S14 Theoretical predictions for ecosystem complexity influences (branching probability) on α, β, and γ diversity in branching networks. In this simulation, environmental variation at headwaters (σ_h) is less than local environmental noise (σ_l). Lines and shades are loess curves fitted to simulated data and its 95% confidence intervals. Each panel represents different ecological scenarios under which metacommunity dynamics were simulated. Rows represent different competition strength. Competitive coefficients (α_{ij}) were varied randomly from 0 to 1.5 (top, strong competition) or 0.75 (bottom, weak competition). Columns represent different dispersal scenarios. Two dispersal parameters were chosen to simulate scenarios with long-distance (the rate parameter of an exponential dispersal kernel $\theta = 0.10$) and short-distance dispersal ($\theta = 1.0$). Other parameters are as follows: dispersal probability $p_d = 0.01$; environmental variation at headwaters $\sigma_h = 0.01$; local environmental noise $\sigma_l = 1$.

References

1. Fukushima, M., Kameyama, S., Kaneko, M., Nakao, K. & Ashley Steel, E. Modelling the effects of dams on freshwater fish distributions in Hokkaido, Japan. *Freshwater Biology* **52**, 1511–1524 (2007).

2. Comte, L. *et al.* RivFishTIME: A global database of fish time-series to study global change ecology in riverine systems. *Global Ecology and Biogeography* **30**, 38–50 (2021).

3. Terui, A. *et al.* Metapopulation stability in branching river networks. *Proceedings of the National Academy of Sciences* **115**, E5963–E5969 (2018).

4. Terui, A. & Miyazaki, Y. Three ecological factors influencing riverine fish diversity in the Shubuto River system, Japan: Habitat capacity, habitat heterogeneity and immigration. *Limnology* **17**, 143–149 (2016).