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SUPPLEMENTARY INFORMATION

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Negative density dependence mediates biodiversity–productivity relationships across scales

Joseph A. LaManna[1]*, R. Travis Belote[2], Laura A. Burkle[3], Christopher P. Catano[1] and Jonathan A. Myers[1]

[1]Department of Biology & Tyson Research Center, Washington University in St. Louis, St. Louis, Missouri, 63130, USA. [2]The Wilderness Society, Bozeman, Montana, 59717, USA. [3]Department of Ecology, Montana State University, Bozeman, Montana, 59717, USA. *e-mail: joe.a.lamanna@gmail.com

Supplementary Information for

Negative Density Dependence Mediates Biodiversity-productivity Relationships Across Scales

Joseph A. LaManna, R. Travis Belote, Laura A. Burkle, Christopher P. Catano, and Jonathan A. Myers
correspondence to: joe.a.lamanna@gmail.com

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Supplementary Table 1. Summary statistics for the 18 FIA ecoregions used in this analysis. US Forest Service ecoregions used in this analysis along with their sample size (*N*, or number of FIA plots per region), mean annual net-primary productivity (NPP), area (km^2), total regional abundance (Total abun.), mean local community abundance (Mean comm. size), multivariate regional environmental heterogeneity (Env. hetero.), mean nearest-neighbour distance of FIA plots within a region (MNND), regional number of species (Reg. rich.), mean local number of species (mean local rich.), median β-diversity (Med. β-div.), median β-diversity after accounting for regional influences (Med. β_{SES}), and the *P*-value (Med. β_{SES} *P*) assessing whether observed median β-diversity was significantly greater than median β-diversity expected from stochastic assembly from the regional-species pool (i.e. proportion of expected median β-diversity values that were greater than or equal to observed median β-diversity).

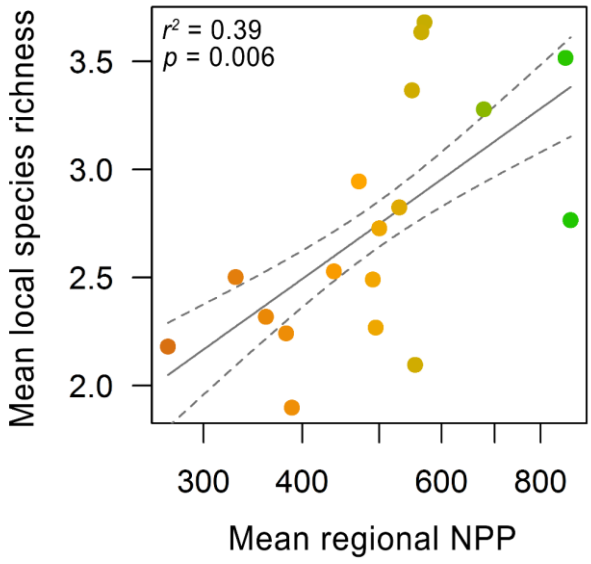
Ecoregion	***N***	**NPP ($gC/m^2/yr$)**	**Area (km^2)**	**Total abun.**	**Mean comm. size**	**Env. hetero.**	**MNND (km)**	**Reg. rich.**	**Mean local rich.**	**Med. β-div.**	**Med. β_{SES}**	**Med. β_{SES} *P***
Coast Ranges	460	873	42,119	11,857	25.8	9.74	5.76	34	2.77	0.846	4.03	< 0.001
Klamath Mountains	492	860	38,057	13,207	26.8	11.76	5.56	40	3.52	0.878	4.50	< 0.001
Western Cascades	1,226	678	44,846	34,928	28.5	9.97	3.79	41	3.28	0.886	5.25	< 0.001
Okanogan Highland	498	571	30,741	15,144	30.4	6.96	4.23	22	3.68	0.846	5.67	< 0.001
Flathead Valley	326	566	21,883	10,131	31.1	6.47	5.35	19	3.63	0.846	6.03	< 0.001
Eastern Cascades	629	555	25,346	13,887	22.1	5.33	3.95	30	2.10	0.875	4.34	< 0.001
Bitterroot Mountains	535	551	24,926	15,140	28.3	5.70	4.91	19	3.37	0.857	5.71	< 0.001
Northern Cascades	709	531	28,793	20,750	29.3	13.42	3.97	29	2.82	0.960	5.87	< 0.001
Blue Mountains	1,025	501	39,876	19,051	18.6	5.43	3.72	25	2.73	0.854	3.87	< 0.001
Belt Mountains	284	495	35,449	10,808	38.1	5.67	6.63	11	2.27	0.892	8.42	< 0.001
Northern Rockies and Bitterroot Valley	294	491	21,810	9,590	32.6	5.73	5.69	12	2.49	0.842	6.79	< 0.001
Northern Rockies	414	471	19,622	12,957	31.3	6.74	4.94	19	2.94	0.824	5.81	< 0.001
Idaho Batholith	858	439	46,586	18,703	21.8	8.55	5.00	18	2.53	0.875	4.80	< 0.001
Modoc Plateau	223	388	23,297	3,511	15.7	4.57	6.13	18	1.90	0.895	3.73	< 0.001
Beaverhead Mountains	324	382	39,428	11,033	34.1	5.36	6.55	11	2.24	0.927	8.28	< 0.001
Yellowstone Highlands	504	360	34,271	13,768	27.3	6.77	5.38	12	2.32	0.905	6.40	< 0.001
Overthrust Mountains	558	330	43,284	13,092	23.5	8.01	5.44	17	2.50	0.946	5.33	< 0.001
Uinta Mountains	233	271	15,644	7,027	30.2	13.60	5.59	13	2.18	1.000	7.84	< 0.001

Supplementary Table 2. Potential regional and confounding influences on β-diversity. Correlations between potential regional and confounding influences on β-diversity and log-transformed mean annual net-primary productivity (NPP) across FIA ecoregions included in this analysis.

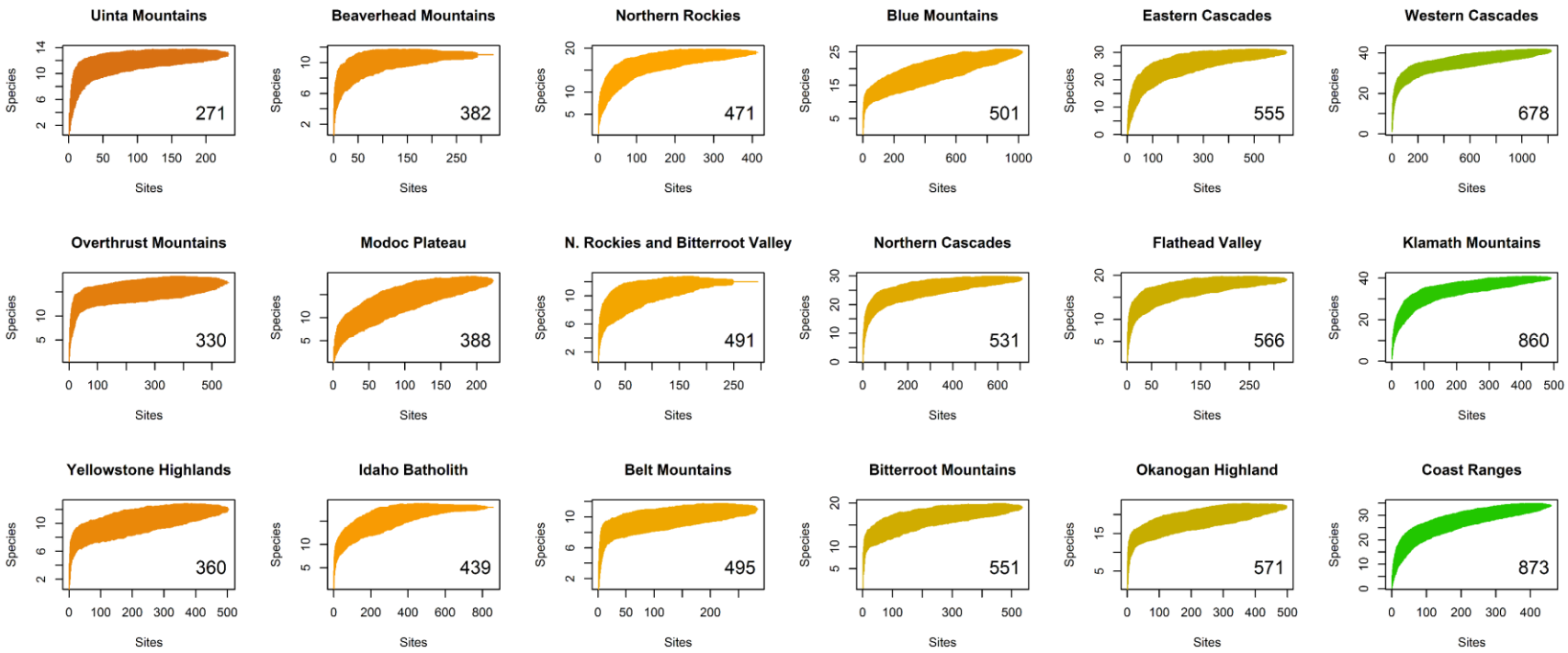
Variable	***r***	***P***
N (number of plots per region)	0.30	0.223
Region area	0.27	0.273
Total region abundance	0.37	0.131
Mean local-community size (mean number of tree individuals per plot per region)	0.04	0.884
Mean nearest FIA plot distance	-0.27	0.284
Mean sapling density (mean number of sapling individuals per plot per region)	-0.06	0.802
β-diversity associated with spatial distance	0.27	0.285

Supplementary Table 3. Estimates of conspecific and heterospecific negative density dependence (CNDD and HNDD) for each ecoregion in this analysis. Estimates and 95% confidence intervals (CI) are provided for effects of conspecific tree density on focal sapling recruitment (CNDD), as well as for effects of both heterospecific tree and sapling densities on focal sapling recruitment (HNDD). Lower values indicate stronger CNDD or HNDD. Regions are ordered by decreasing mean annual net-primary productivity (NPP).

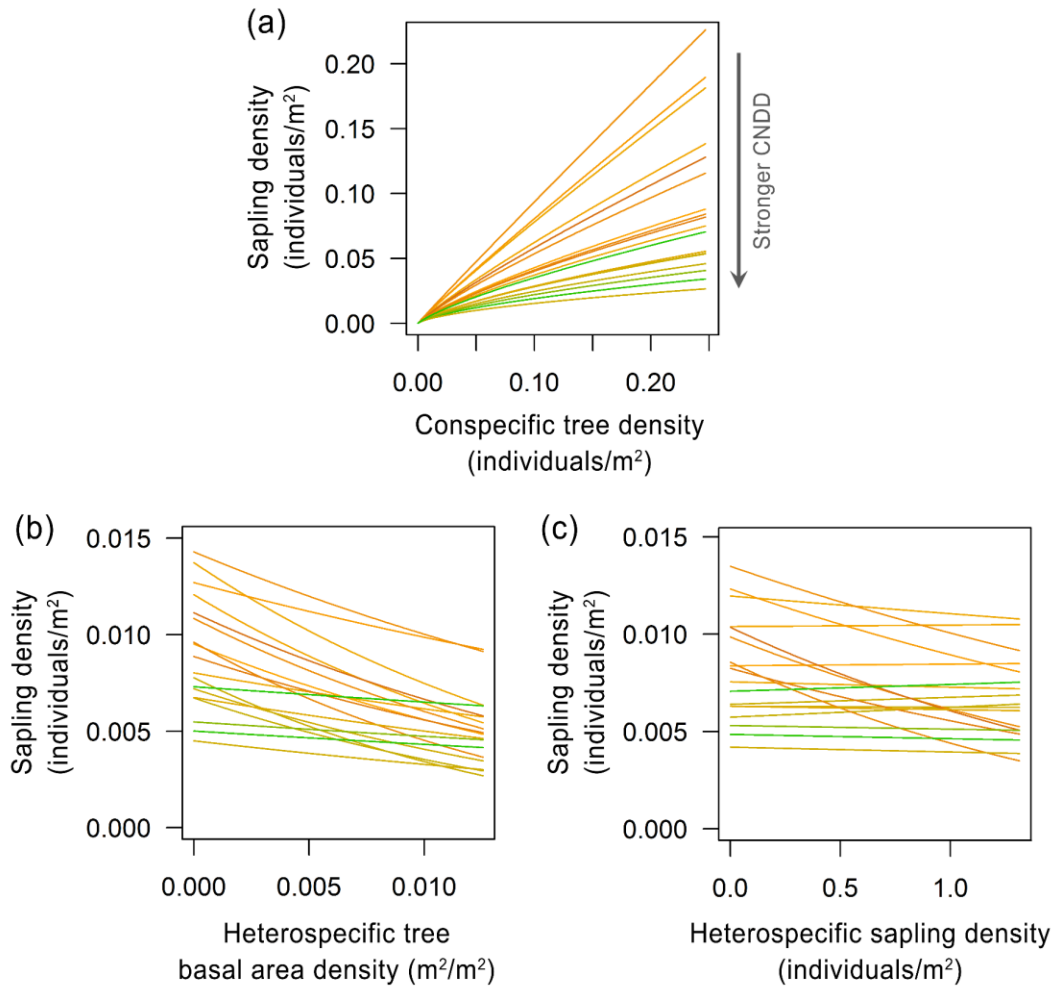
Region	CNDD	95% CI	HNDD from heterospecific trees	95% CI	HNDD from heterospecific saplings	95% CI
Coast Ranges	0.755	(0.568,0.942)	-0.006	(-0.013,0.000)	0.002	(-0.003,0.007)
Klamath Mountains	0.615	(0.481,0.748)	-0.008	(-0.013,-0.002)	-0.002	(-0.006,0.002)
Western Cascades	0.650	(0.521,0.778)	-0.008	(-0.010,-0.005)	-0.001	(-0.004,0.001)
Okanogan Highland	0.667	(0.539,0.794)	-0.034	(-0.041,-0.026)	0.003	(-0.009,0.016)
Flathead Valley	0.689	(0.510,0.867)	-0.043	(-0.053,-0.034)	0.002	(-0.019,0.024)
Eastern Cascades	0.569	(0.414,0.723)	-0.016	(-0.035,0.004)	-0.002	(-0.006,0.001)
Bitterroot Mountains	0.698	(0.522,0.873)	-0.031	(-0.038,-0.024)	0.000	(-0.007,0.007)
Northern Cascades	0.708	(0.580,0.836)	-0.016	(-0.021,-0.012)	-0.001	(-0.005,0.003)
Blue Mountains	0.760	(0.600,0.920)	-0.015	(-0.019,-0.010)	-0.002	(-0.008,0.005)
Belt Mountains	0.930	(0.782,1.077)	-0.036	(-0.067,-0.006)	-0.003	(-0.018,0.011)
Northern Rockies and Bitterroot Valley	0.876	(0.680,1.072)	-0.037	(-0.071,-0.002)	0.000	(-0.013,0.014)
Northern Rockies	0.783	(0.585,0.982)	-0.030	(-0.049,-0.011)	0.000	(-0.007,0.008)
Idaho Batholith	0.943	(0.656,1.230)	-0.015	(-0.021,-0.010)	-0.014	(-0.026,-0.001)
Modoc Plateau	0.976	(0.708,1.243)	-0.022	(-0.037,-0.006)	-0.013	(-0.027,0.002)
Beaverhead Mountains	0.843	(0.725,0.962)	-0.034	(-0.048,-0.020)	-0.020	(-0.033,-0.006)
Yellowstone Highlands	0.780	(0.628,0.932)	-0.042	(-0.052,-0.031)	-0.026	(-0.036,-0.016)
Overthrust Mountains	0.774	(0.591,0.957)	-0.026	(-0.048,-0.005)	-0.016	(-0.024,-0.008)
Uinta Mountains	0.865	(0.719,1.012)	-0.030	(-0.042,-0.017)	-0.022	(-0.034,-0.010)



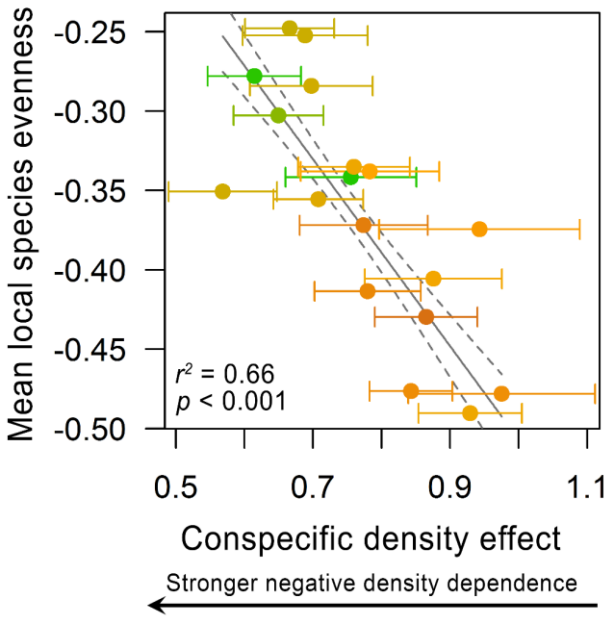
Supplementary Figure 1. Relationship between net-primary productivity (NPP) and local species richness across ecoregions. Mean local species richness increased with mean annual NPP across regions. Each point is an ecoregion and coloured according to its mean annual NPP. Statistics are from linear regression tests. Best-fit linear relationship (± 1 SE) is shown in grey.



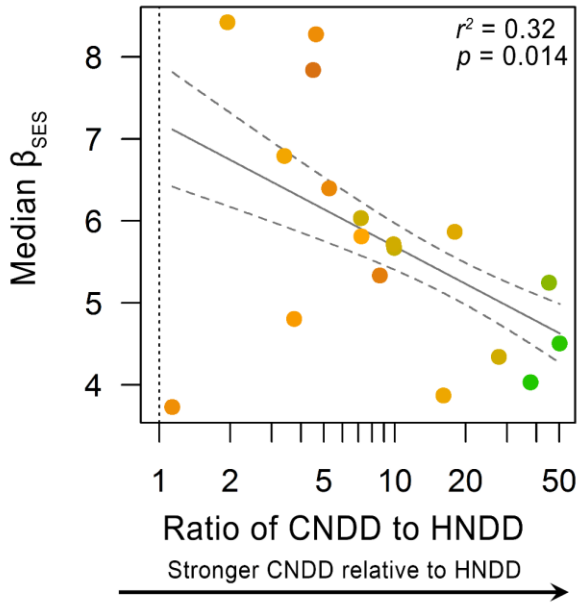
Supplementary Figure 2. Species accumulation curves for each FIA ecoregion arranged according to mean annual net-primary productivity (NPP). Species accumulation curves present the accumulation of additional species with increasing number of FIA plots (i.e., sites or samples) in each region. Asymptotic or nearly asymptotic curves represent adequate sampling of regional species richness. Mean annual NPP of a region increases across panels from left to right. Mean annual NPP of each region is shown in the lower-right corner of each graph, and regions are coloured according to their mean annual NPP.



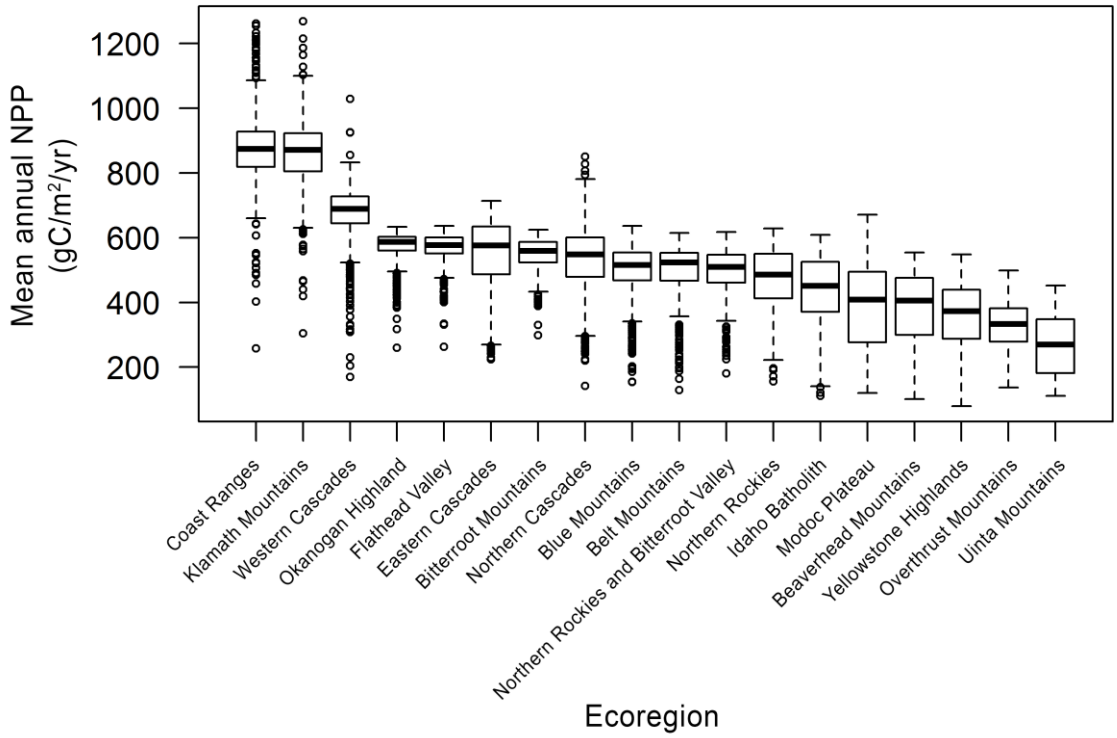
Supplementary Figure 3. Mean relationships between sapling densities and their conspecific and heterospecific densities in each of the 18 ecoregions. (a) Conspecific negative density dependence (CNDD) was calculated for each region as the mean reduction in per-capita recruitment with increasing conspecific tree density across species. Per-capita recruitment was calculated as the mean slope between conspecific tree and sapling densities. Conspecific tree and sapling densities were log-transformed to estimate the proportional (and not additive) change in sapling densities with increasing conspecific tree densities. More productive regions had stronger CNDD than less productive regions. (b) Density dependence from heterospecific trees (b) and heterospecific saplings (c) was calculated for each region as the mean slope between focal sapling densities and local heterospecific tree basal area or local heterospecific sapling densities, respectively, across species. Regions differed in the slopes of these relationships as well, with less productive regions having stronger HNDD from trees and saplings (more negative slopes). However, effects of heterospecific tree density on focal sapling density were stronger (more negative) than effects from heterospecific saplings, with 16 heterospecific tree slopes but only five heterospecific sapling slopes significantly different from zero. All relationships were calculated from one model per region and are shown at mean values of other variables (e.g., CNDD is shown at mean heterospecific tree basal area and heterospecific sapling density). Each line represents the mean relationship for each ecoregion and is coloured according to its mean annual net-primary productivity (NPP).



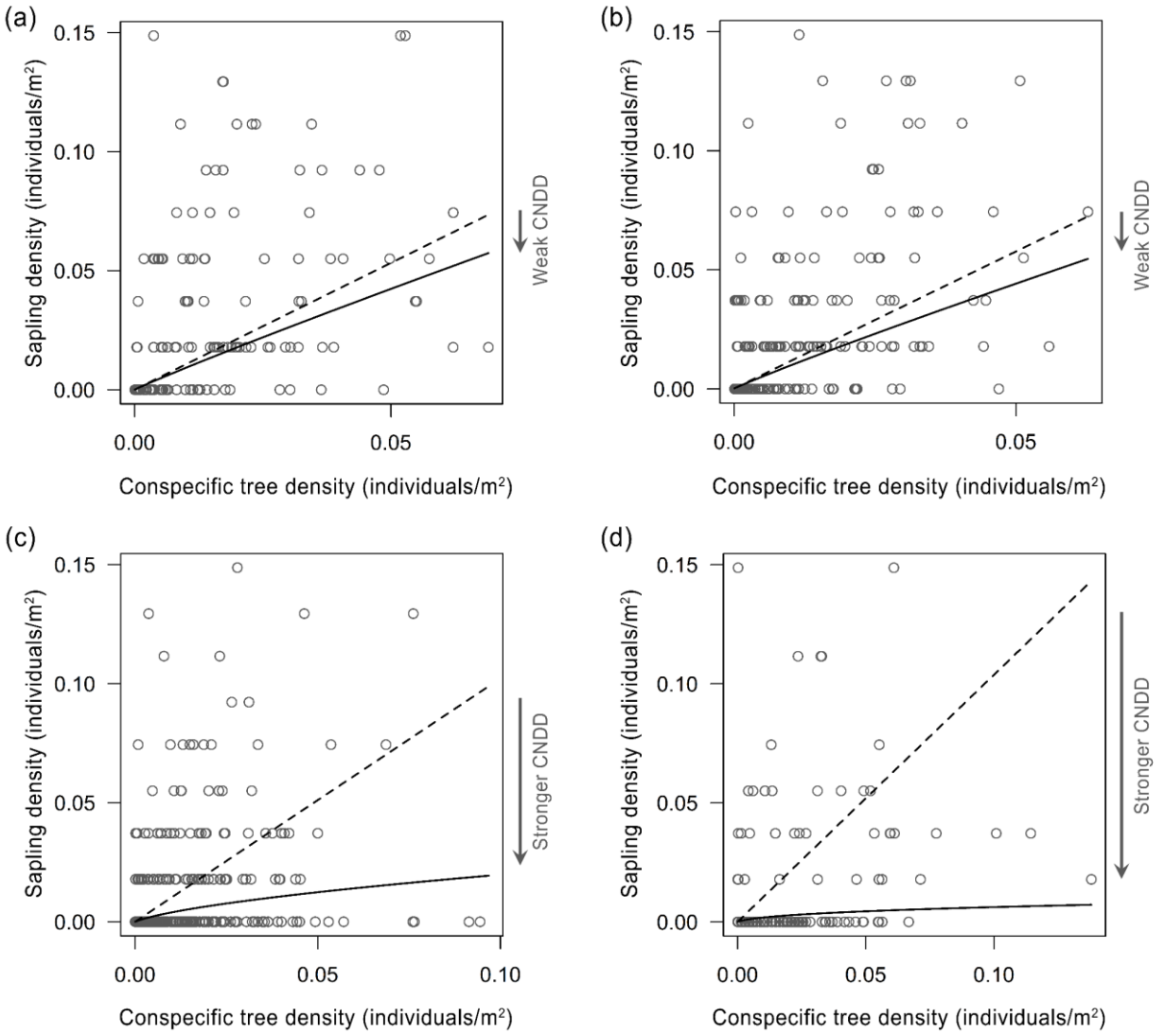
Supplementary Figure 4. Relationship between the strength of conspecific negative density dependence (CNDD) and local species evenness. Mean local species evenness increased with the mean strength of CNDD across regions. Mean local species evenness was measured as the mean slope between local species relative abundance (log-transformed) and local species abundance rank for all FIA plots in each region (i.e., mean slope of local FIA plot rank-abundance curves for each region). Each point is an ecoregion and coloured according to its mean annual net-primary productivity (NPP). Measures of CNDD represent means across all species in a region. Statistics are from linear regression tests. Best-fit linear relationship (± 1 SE) is shown in grey.



Supplementary Figure 5. Relationship between the ratio of conspecific to heterospecific negative density dependence (CNDD:HNDD) and β-diversity. Stronger CNDD relative to HNDD was associated with lower β-diversity (β_{SES}). Each point is an ecoregion and coloured according to its mean annual net-primary productivity (NPP). Measures of CNDD and HNDD represent means across all species in a region. The dotted line indicates a ratio of CNDD to HNDD of one, or where CNDD and HNDD have equivalent strength. Note the logarithmic scale for the ratio of CNDD to HNDD. Statistics are from linear regression tests. Best-fit linear relationship (± 1 SE) is shown in grey.



Supplementary Figure 6. Variation in mean annual net-primary productivity (NPP) within and across US Forest Service FIA ecoregions used in this analysis. Quartile boxplots showing the median (black bar), 25th and 75th percentiles (first and third quartiles; open box), and extreme values (whiskers and points) of NPP within each ecoregion. Regions are ordered according to descending mean annual NPP. According to an ANOVA test, ecoregion identity explained 72.7% of total variation in NPP across all 9,592 FIA plots used in this analysis.



Supplementary Figure 7. Example estimation of conspecific negative density dependence (CNDD). All panels show Douglas-fir (*Pseudotsuga menziesii*, Pinaceae) sapling densities (individuals/m^2) against conspecific tree densities (individuals/m^2) across FIA plots for four ecoregions. Best-fit curves for density-dependent sapling recruitment (saplings/tree) are shown as a solid line in each panel. Models simultaneously estimated per-capita recruitment at low densities (represented here as the slope of the dashed line in each panel), and estimated CNDD as the reduction in per-capita recruitment with increasing conspecific tree densities (reflected in the distance between the dashed line and solid line in each panel). CNDD for this species was relatively weak in (a) the Northern Rockies and Bitterroot Valley and (b) Flathead Valley regions, as indicated by little reduction in per-capita recruitment with increasing conspecific tree densities. In contrast, CNDD for the same species was relatively stronger in (c) the Northern Cascades and even stronger in (d) the Coast Ranges, as indicated by substantial reduction in per-capita recruitment with increasing conspecific tree densities. Log-transformed tree and sapling densities were used to fit curves, but densities are shown on an untransformed axis here for ease of visualization.