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SUPPLEMENTARY INFORMATION

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A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change

Jian Song[1,2], Shiqiang Wan[1,2*], Shilong Piao[3,4,5], Alan K. Knapp[6,7], Aimée T. Classen[8,9], Sara Vicca[10], Philippe Ciais[11,3], Mark J. Hovenden[12], Sebastian Leuzinger[13], Claus Beier[14], Paul Kardol[15], Jianyang Xia[16,17], Qiang Liu[3], Jingyi Ru[2], Zhenxing Zhou[2], Yiqi Luo[18], Dali Guo[19], J. Adam Langley[20], Jakob Zscheischler[21,22], Jeffrey S. Dukes[23], Jianwu Tang[24], Jiquan Chen[25], Kirsten S. Hofmockel[26,27], Lara M. Kueppers[28,29], Lindsey Rustad[30], Lingli Liu[31], Melinda D. Smith[6,7], Pamela H. Templer[32], R. Quinn Thomas[33], Richard J. Norby[34], Richard P. Phillips[35], Shuli Niu[36], Simone Fatichi[37], Yingping Wang[38], Pengshuai Shao[39], Hongyan Han[39], Dandan Wang[2], Lingjie Lei[2], Jiali Wang[2], Xiaona Li[2], Qian Zhang[2], Xiaoming Li[2], Fanglong Su[2], Bin Liu[2], Fan Yang[2], Gaigai Ma[2], Guoyong Li[2], Yanchun Liu[2], Yinzhan Liu[2], Zhongling Yang[2], Kesheng Zhang[2], Yuan Miao[2], Mengjun Hu[2], Chuang Yan[2], Ang Zhang[2], Mingxing Zhong[2], Yan Hui[2], Ying Li[2] and Mengmei Zheng[2]

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[1]College of Life Sciences, Hebei University, Baoding, China[2]International Joint Research Laboratory for Global Change Ecology, School of Life Sciences, Henan University, Kaifeng, China. [3]Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing, China. [4]Key Laboratory of Alpine Ecology, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China. [5]Center for Excellence in Tibetan Earth Science, Chinese Academy of Sciences, Beijing, China. [6]Department of Biology, Colorado State University, Fort Collins, CO, USA. [7]Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO, USA. [8]Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT, USA. [9]Gund Institute for Environment, University of Vermont, Burlington, VT, USA. [10]Centre of Excellence PLECO (Plant and Vegetation Ecology), Department of Biology, University of Antwerp, Wilrijk, Belgium. [11]Laboratoire des Sciences du Climat et de l'Environnement, Gif sur Yvette, France. [12]Biological Sciences, School of Natural Sciences, University of Tasmania, Hobart, Australia. [13]Institute for Applied Ecology New Zealand, School of Science, Auckland University of Technology, Auckland, New Zealand. [14]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark. [15]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden. [16]Zhejiang Tiantong Forest Ecosystem National Observation and Research Station, Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, East China Normal University, Shanghai, China. [17]Research Center for Global Change and Ecological Forecasting, East China Normal University, Shanghai, China. [18]Center for Ecosystem Study and Society, Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ, USA. [19]Center for Forest Ecosystem Studies and Qianyanzhou Ecological Station, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. [20]Department of Biology, Villanova University, Villanova, PA, USA. [21]Institute for Atmospheric and Climate Science, ETH, Zürich, Switzerland. [22]Climate and Environmental Physics, University of Bern, Bern, Switzerland. [23]Department of Forestry and Natural Resources and Department of Biological Sciences, Purdue University, West Lafayette, IN, USA. [24]Marine Biological Laboratory, The Ecosystem Center, Woods Hole, MA, USA. [25]Center for Global Change and Earth Observations, Department of Geography, Environment and Spatial Sciences, Michigan State University, East Lansing, MI, USA. [26]Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, IA, USA. [27]Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory, Richland, WA, USA. [28]Energy and Resources Group, University of California, Berkeley, Berkeley, CA, USA. [29]Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [30]United States Department of Agriculture Forest Service, Northern Research Station, Durham, NH, USA. [31]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing, China. [32]Department of Biology, Boston University, Boston, MA, USA. [33]Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA, USA. [34]Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA. [35]Department of Biology, Indiana University, Bloomington, IN, USA. [36]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China. [37]Institute of Environmental Engineering, ETH, Zurich, Switzerland. [38]CSIRO Oceans and Atmosphere, Victoria, Australia. [39]Shandong Key Laboratory of Eco-Environmental Science for the Yellow River Delta, Binzhou University, Binzhou, China. *e-mail: swan@ibcas.ac.cn

Supplementary Information for

A meta-analysis of 1119 manipulative experiments on terrestrial carbon cycling responses to global change

Jian Song[1,2], Shiqiang Wan[1,2*], Shilong Piao[3,4,5], Alan K. Knapp[6,7], Aimée T. Classen[8,9], Sara Vicca[10], Philippe Ciais[11,3], Mark J. Hovenden[12], Sebastian Leuzinger[13], Claus Beier[14], Paul Kardol[15], Jianyang Xia[16,17], Qiang Liu[3], Jingyi Ru[2], Zhenxing Zhou[2], Yiqi Luo[18], Dali Guo[19], J. Adam Langley[20], Jakob Zscheischler[21,22], Jeffrey S. Dukes[23], Jianwu Tang[24], Jiquan Chen[25], Kirsten S. Hofmockel[26,27], Lara M. Kueppers[28,29], Lindsey Rustad[30], Lingli Liu[31], Melinda D. Smith[6,7], Pamela H. Templer[32], R. Quinn Thomas[33], Richard J. Norby[34], Richard P. Phillips[35], Shuli Niu[36], Simone Fatichi[37], Yingping Wang[38], Pengshuai Shao[39], Hongyan Han[39], Dandan Wang[2], Lingjie Lei[2], Jiali Wang[2], Xiaona Li[2], Qian Zhang[2], Xiaoming Li[2], Fanglong Su[2], Bin Liu[2], Fan Yang[2], Gaigai Ma[2], Guoyong Li[2], Yanchun Liu[2], Yinzhan Liu[2], Zhongling Yang[2], Kesheng Zhang[2], Yuan Miao[2], Mengjun Hu[2], Chuang Yan[2], Ang Zhang[2], Mingxing Zhong[2], Yan Hui[2], Ying Li[2] and Mengmei Zheng[2]

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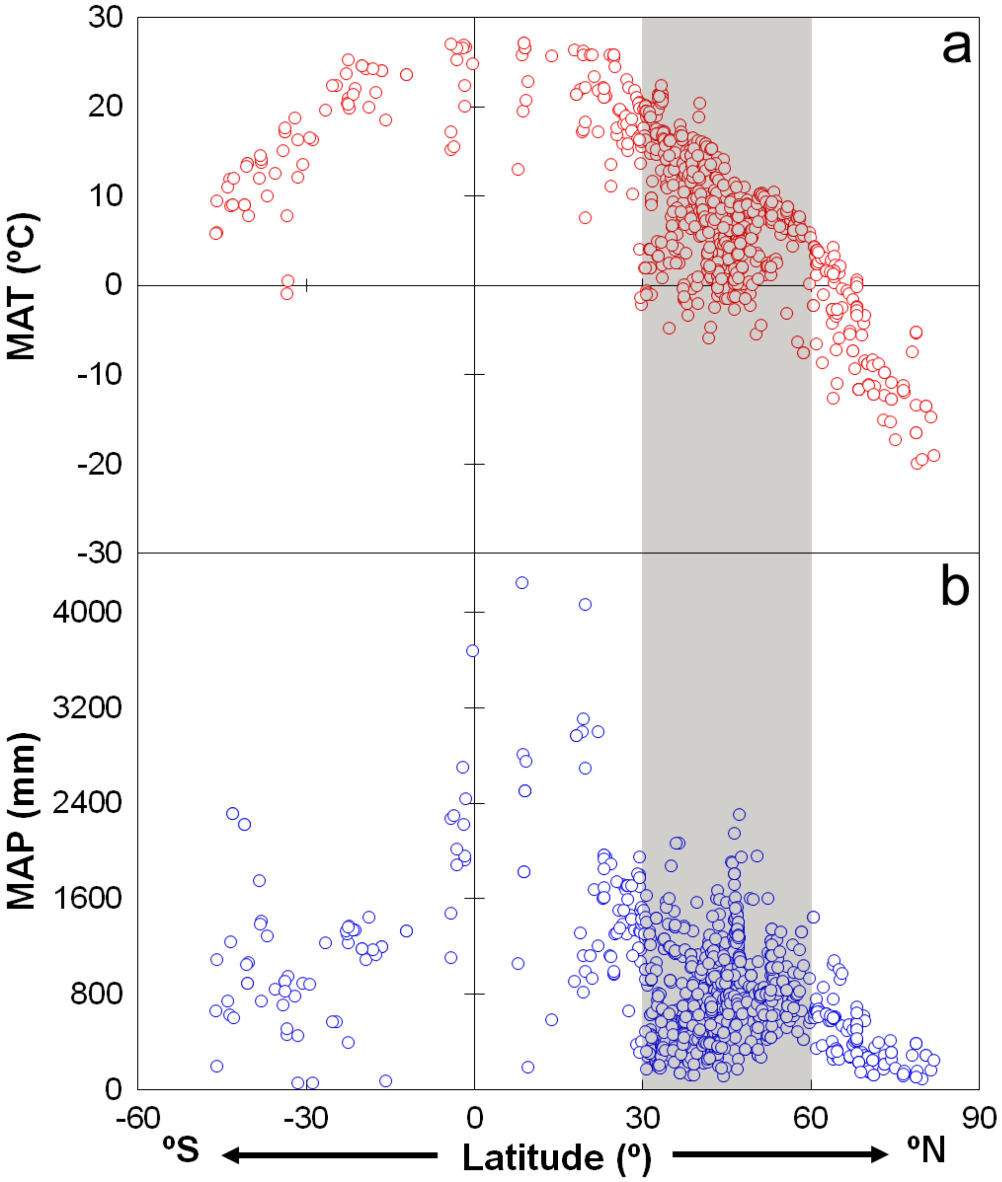

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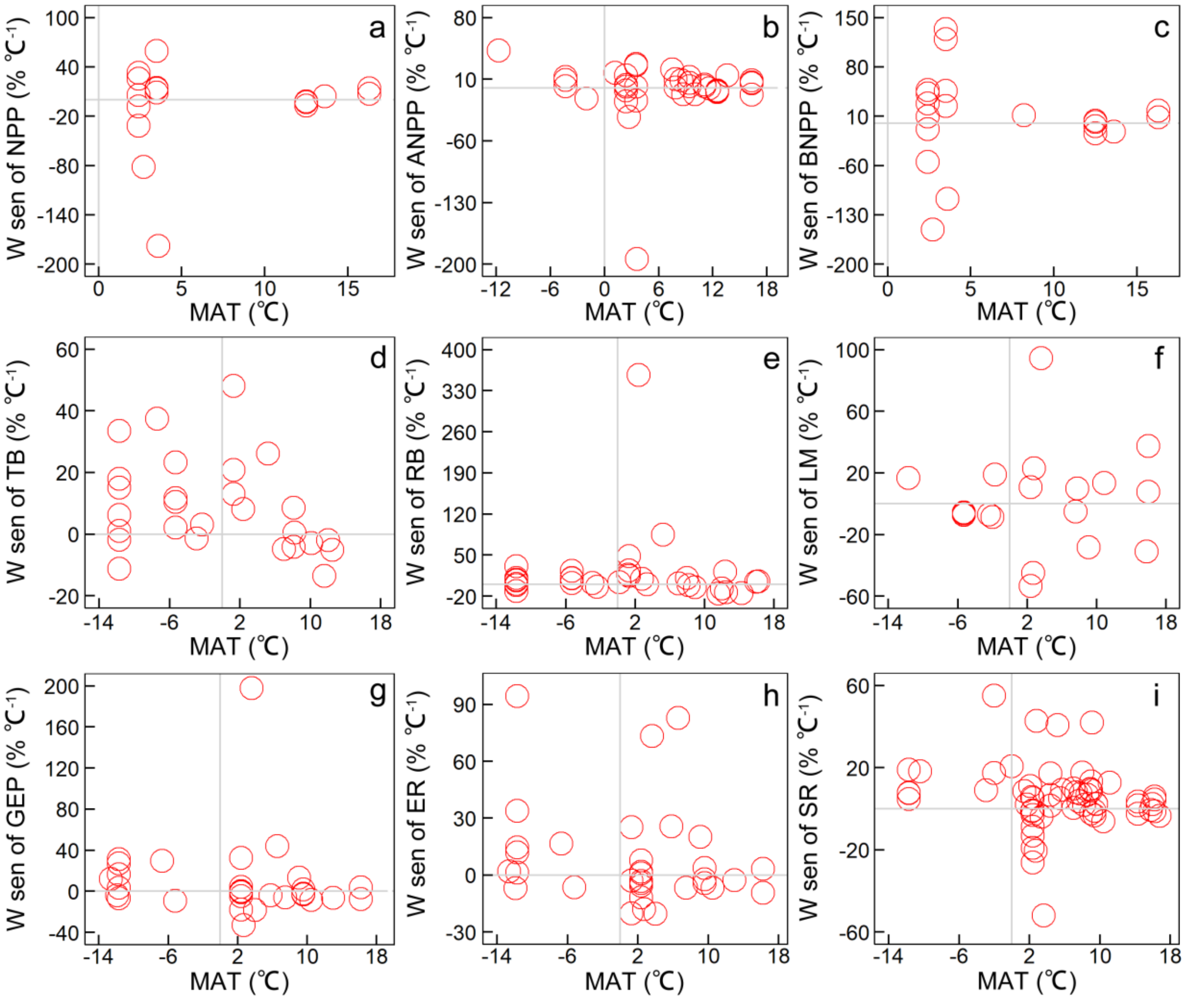

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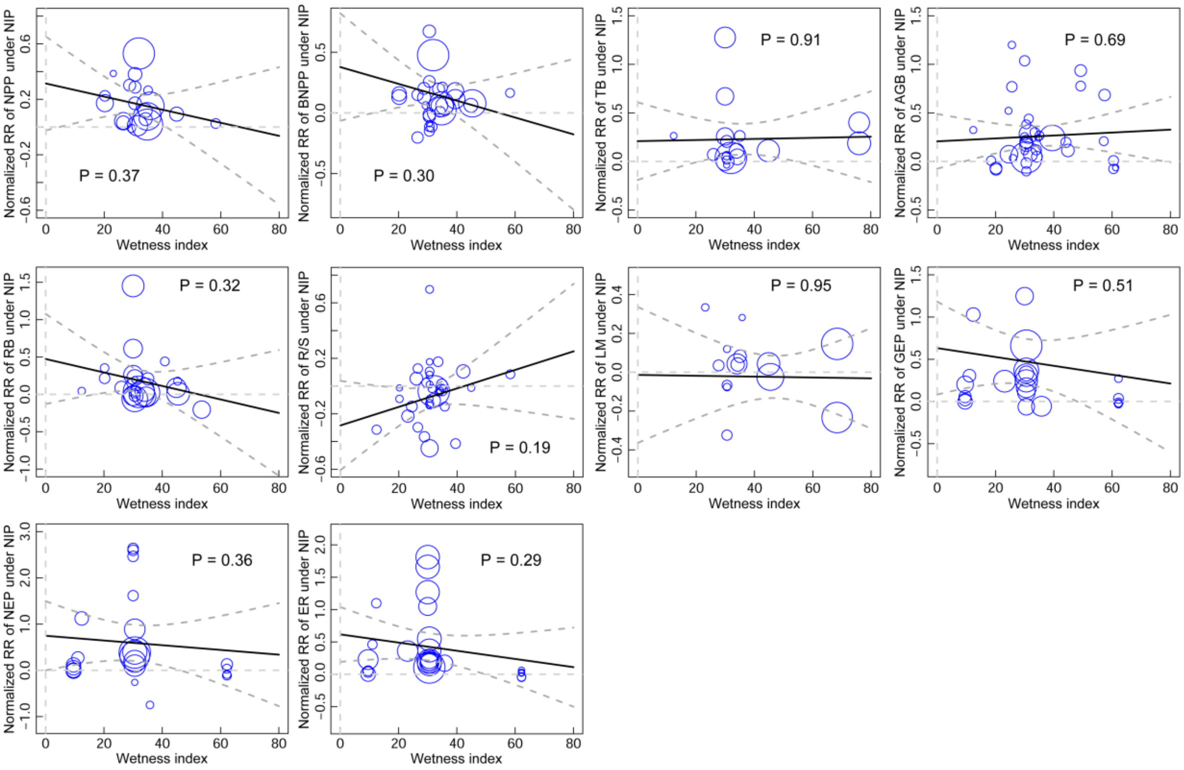

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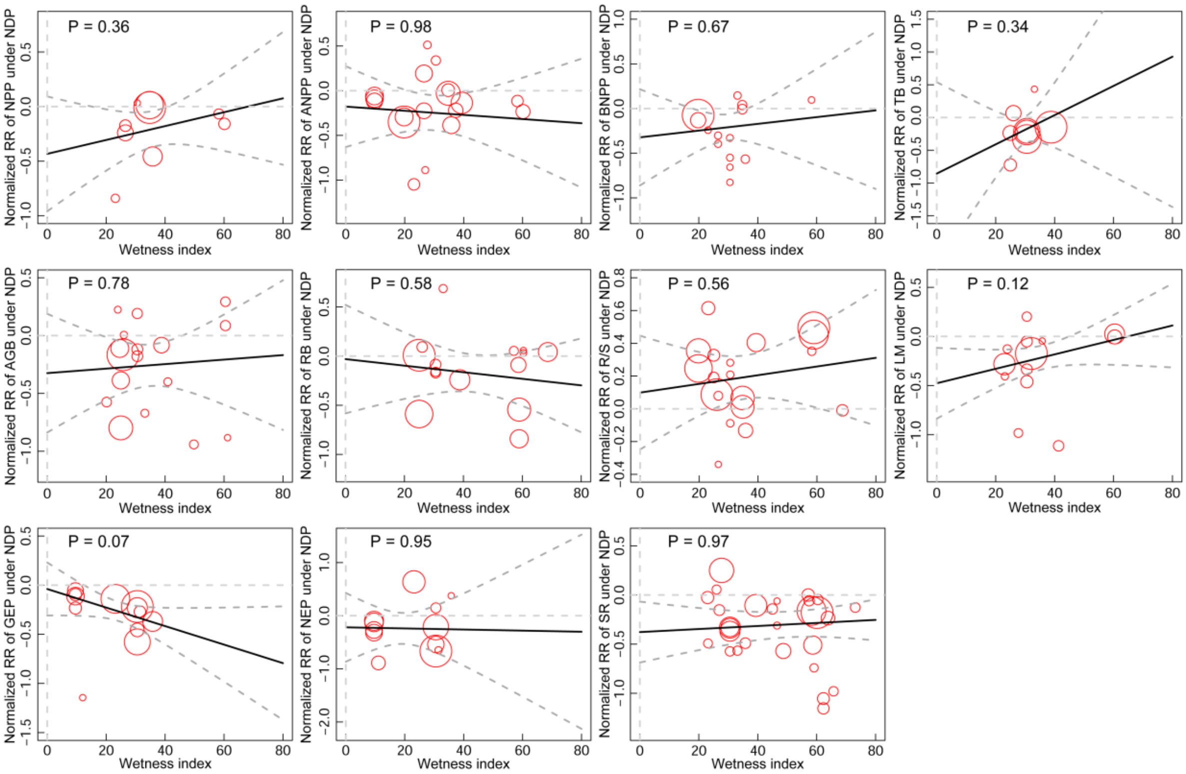
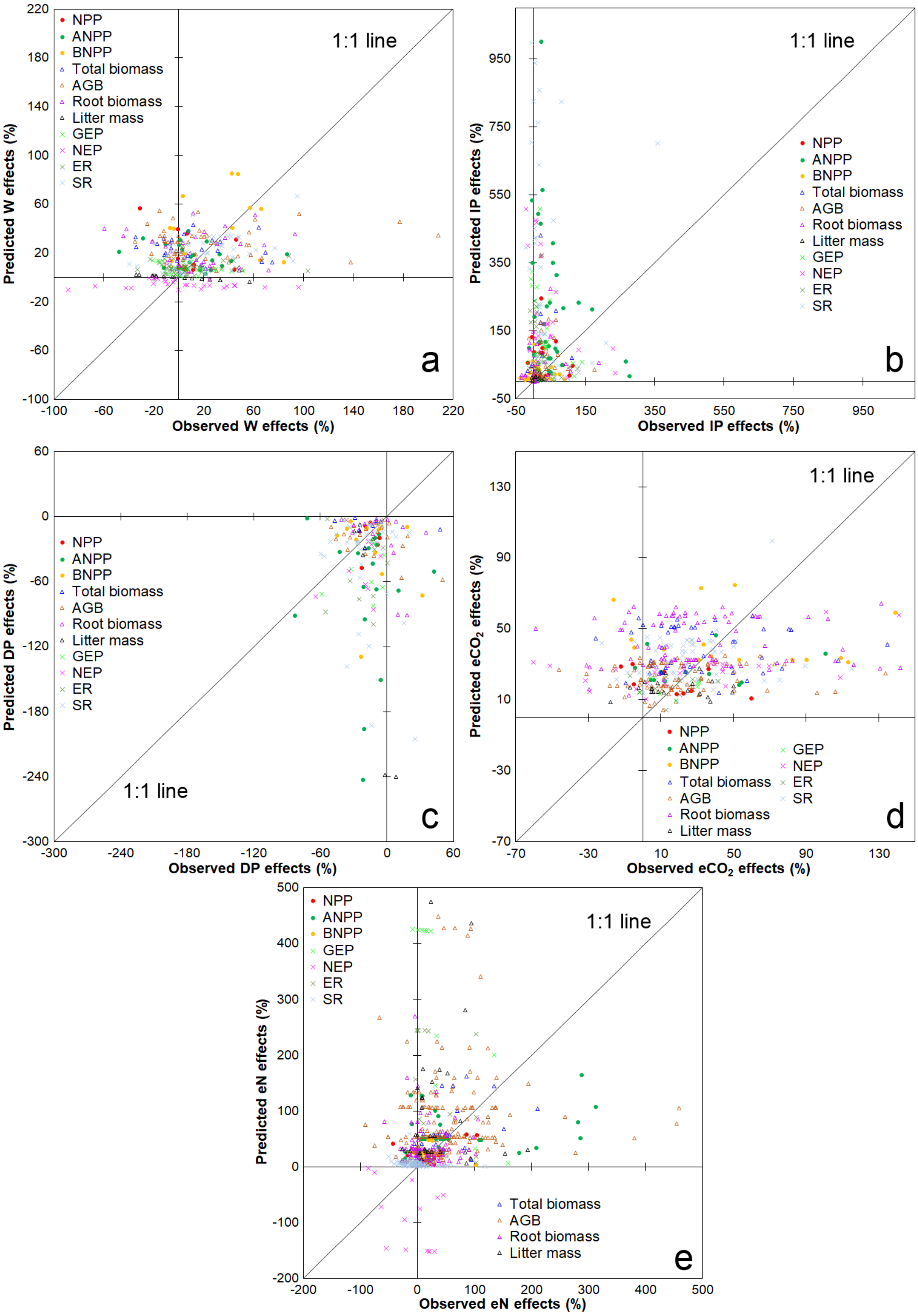
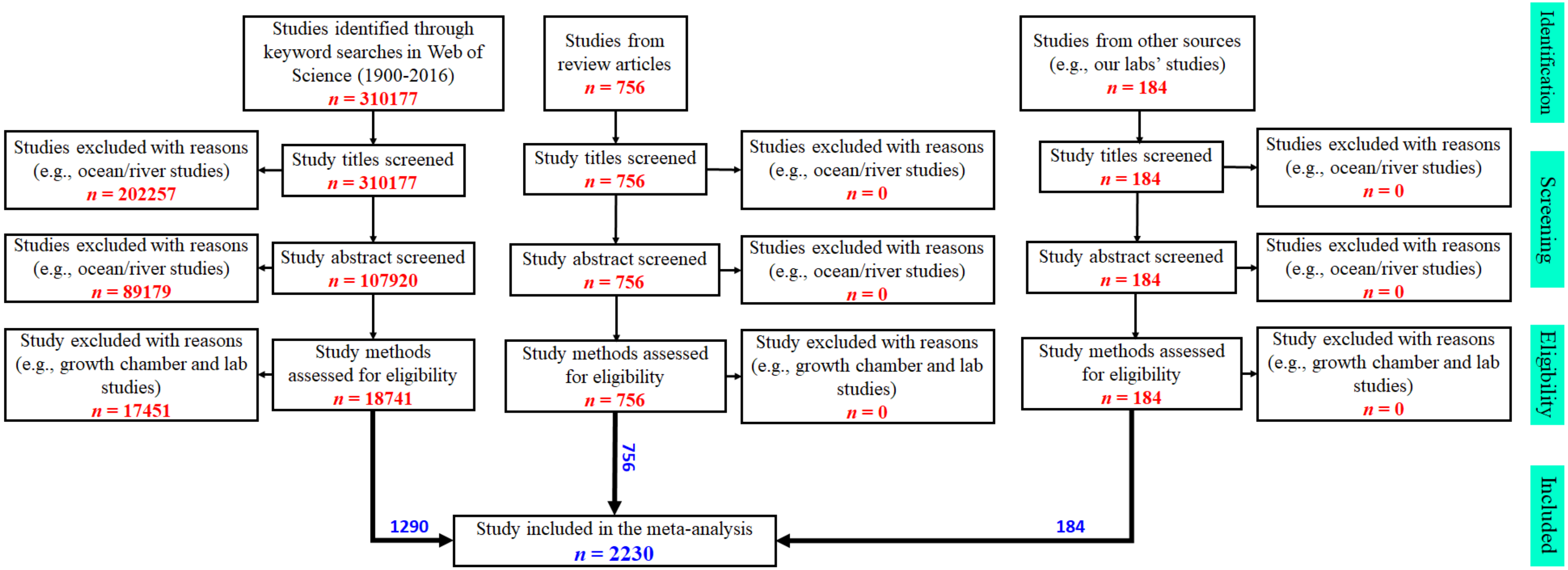


Supplementary Figure 5. Observed effects against predicted effects of global change drivers. The predicted against their observed effects of warming (W), increased precipitation (IP), decreased precipitation (DP), elevated CO$_2$ (eCO$_2$), and nitrogen addition (eN) on ecosystem carbon-cycle variables in each experiment (see Methods for details). Points on the 1:1 line indicate perfect predictions. See Supplementary Figures 2 and 3 for variable abbreviations. Results showed that it is difficult to predict the ecosystem responses at a site using the mean sensitivities calculated from the other experiments, suggesting a poor predictive ability of our sensitivity database.



Supplementary Figure 6. Publication compilation. Study selection for inclusion in the global synthesis.



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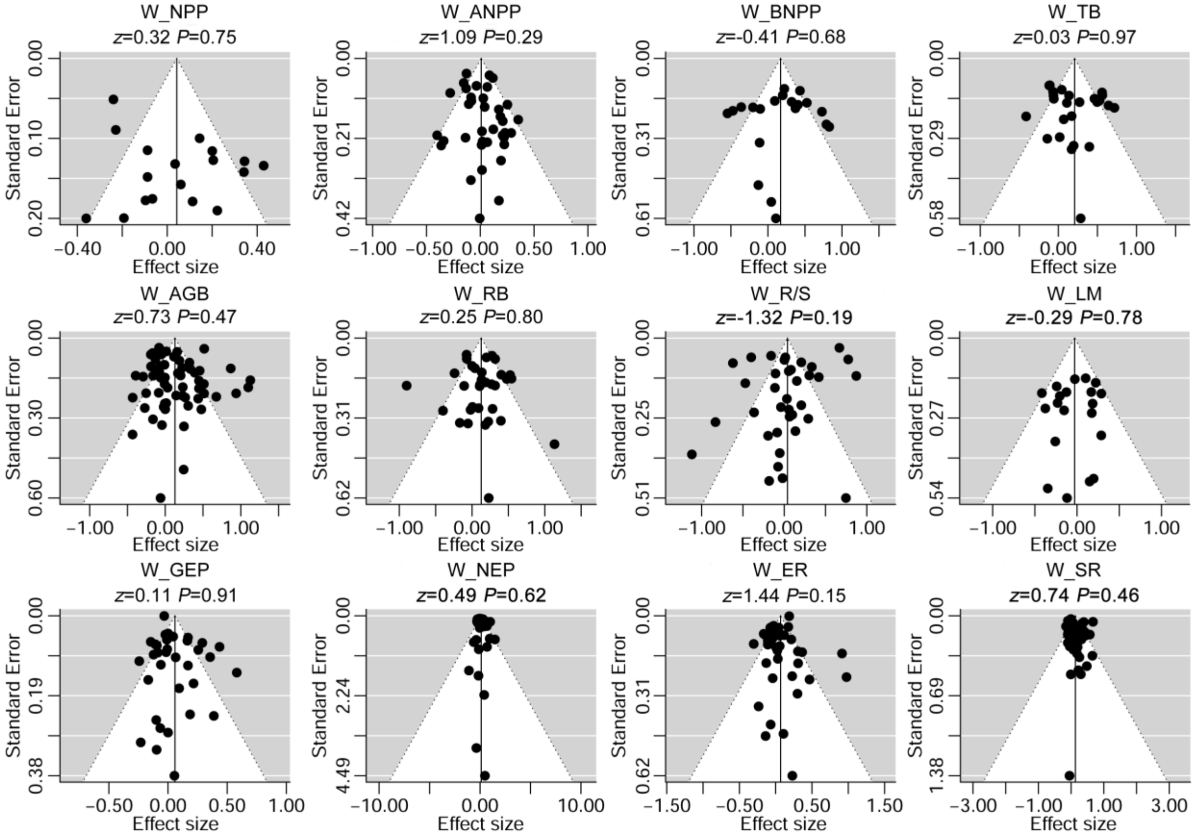

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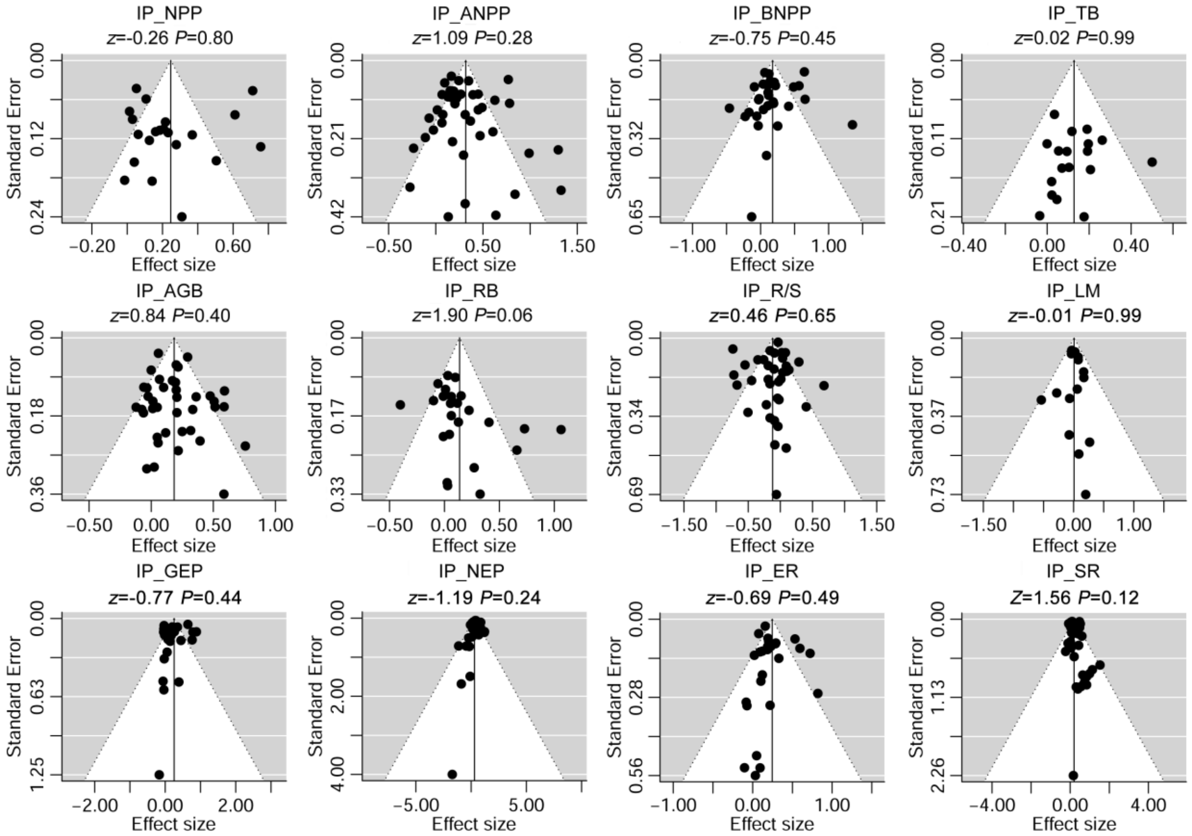

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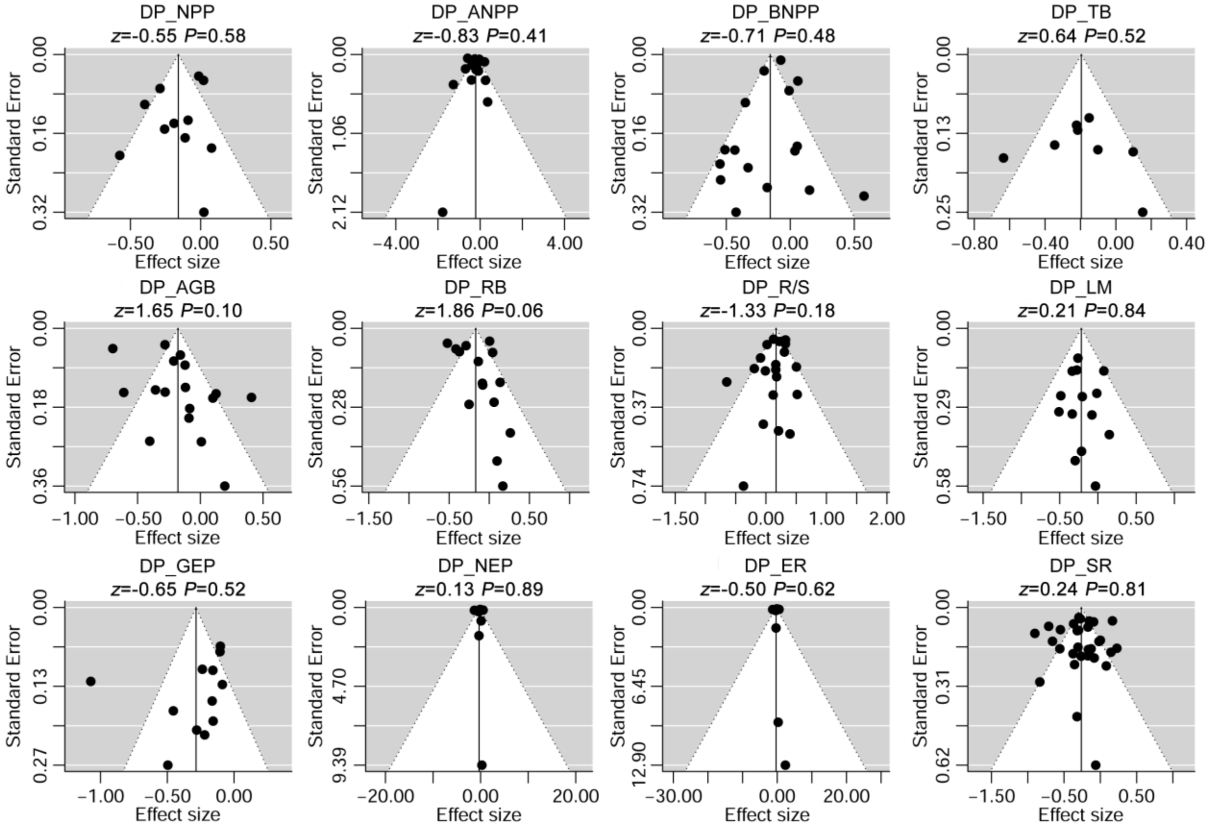

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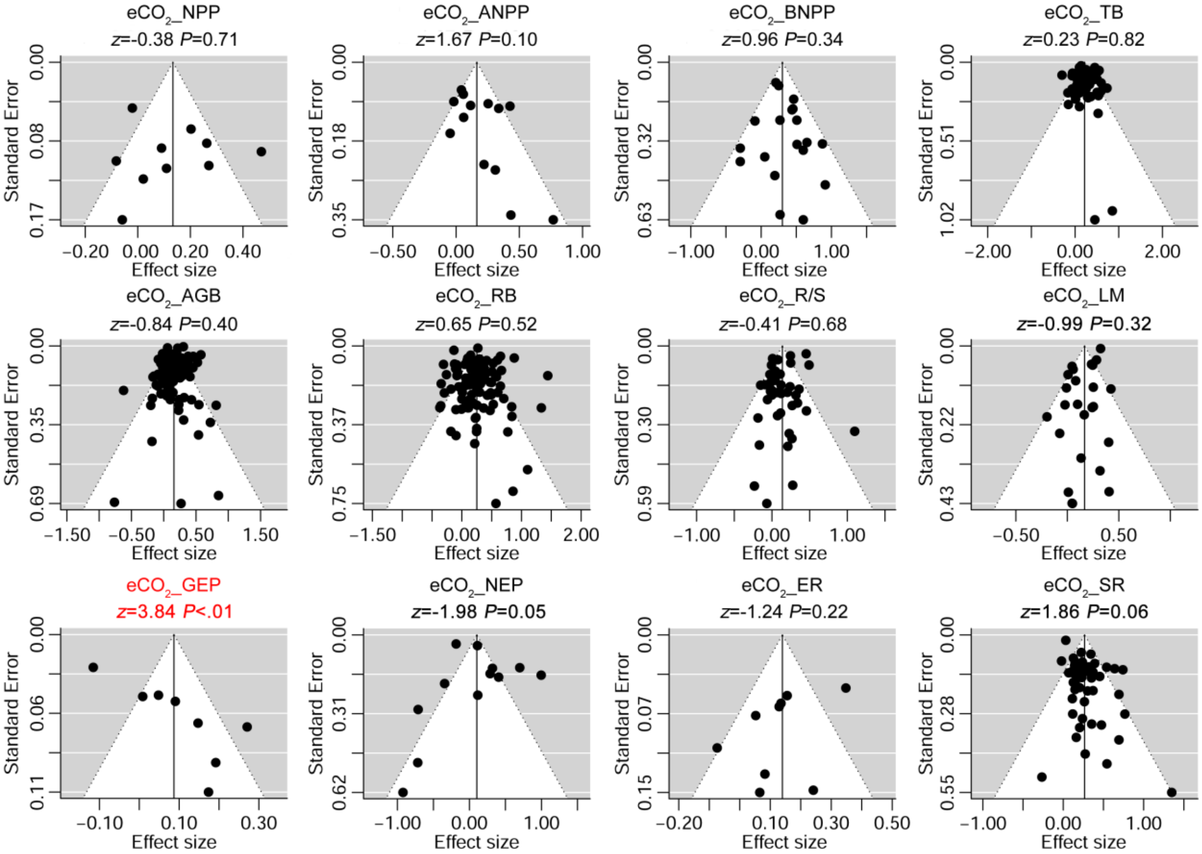

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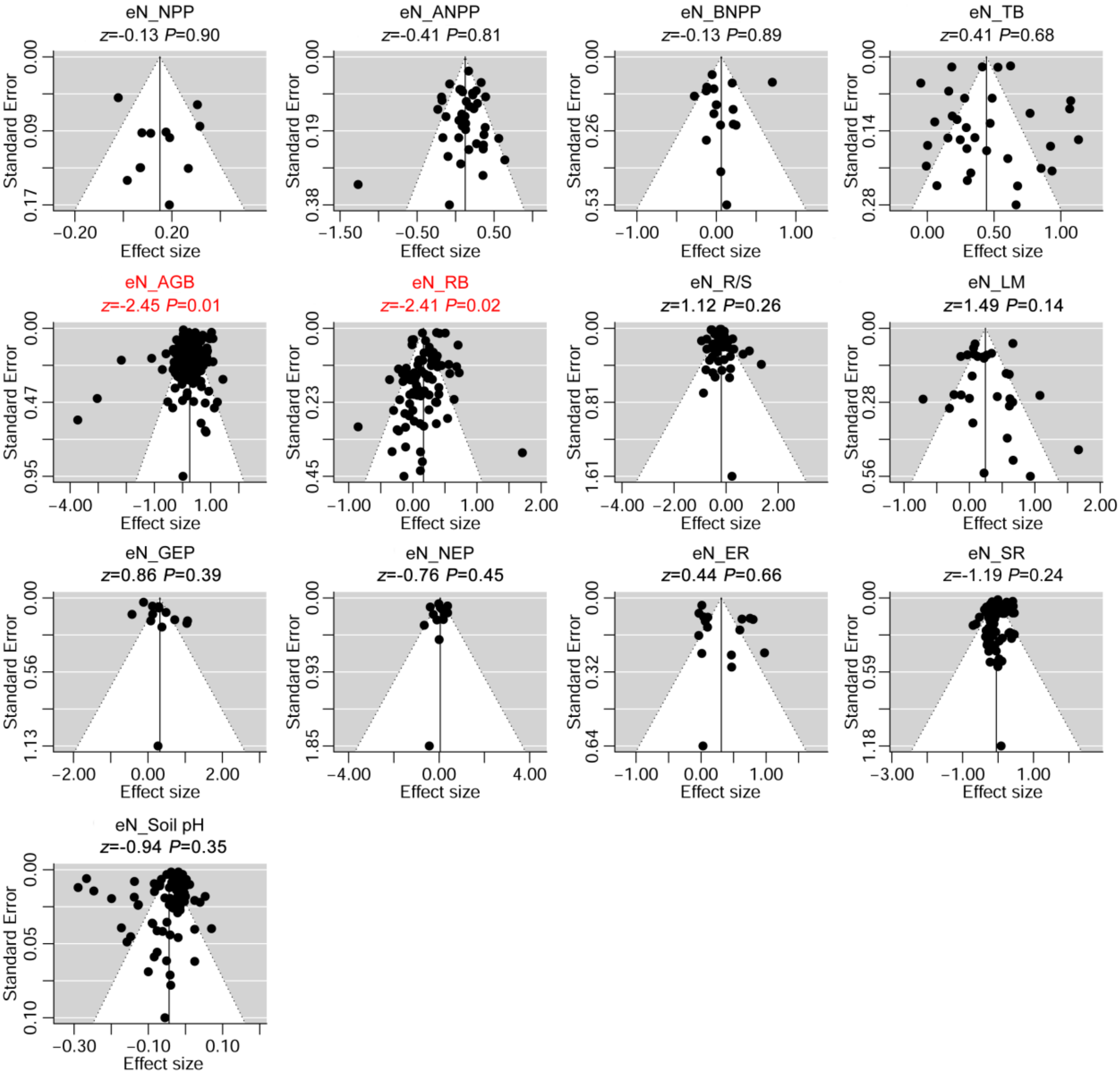

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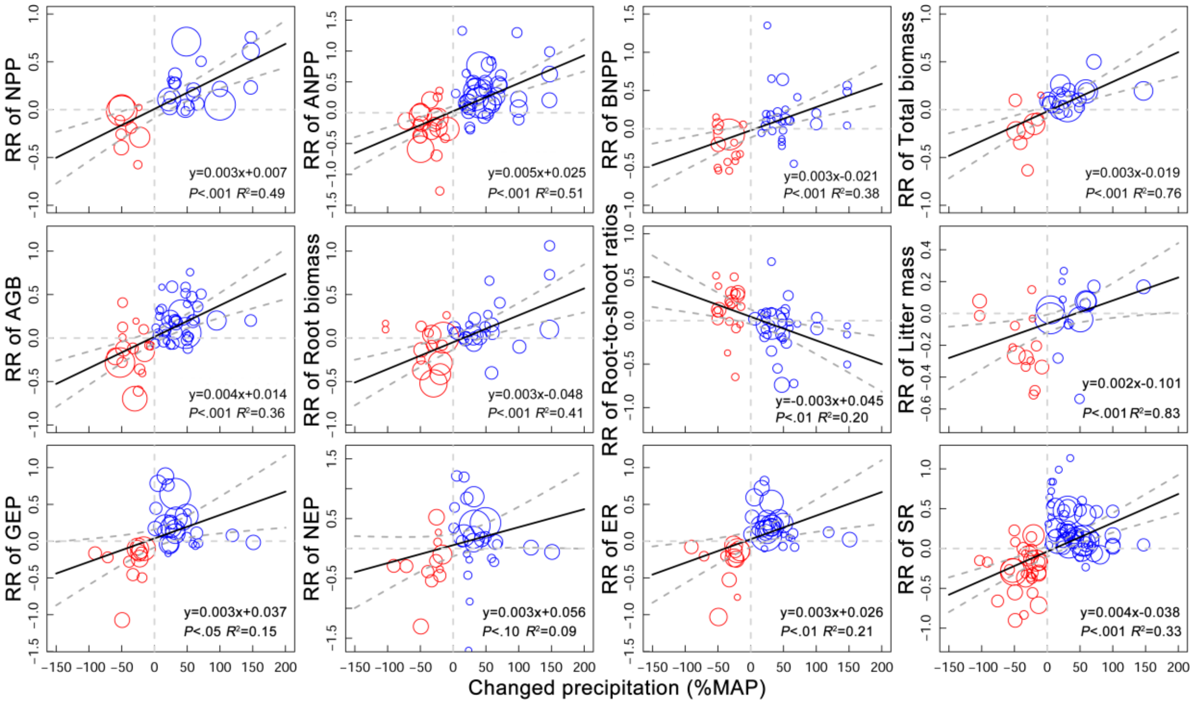

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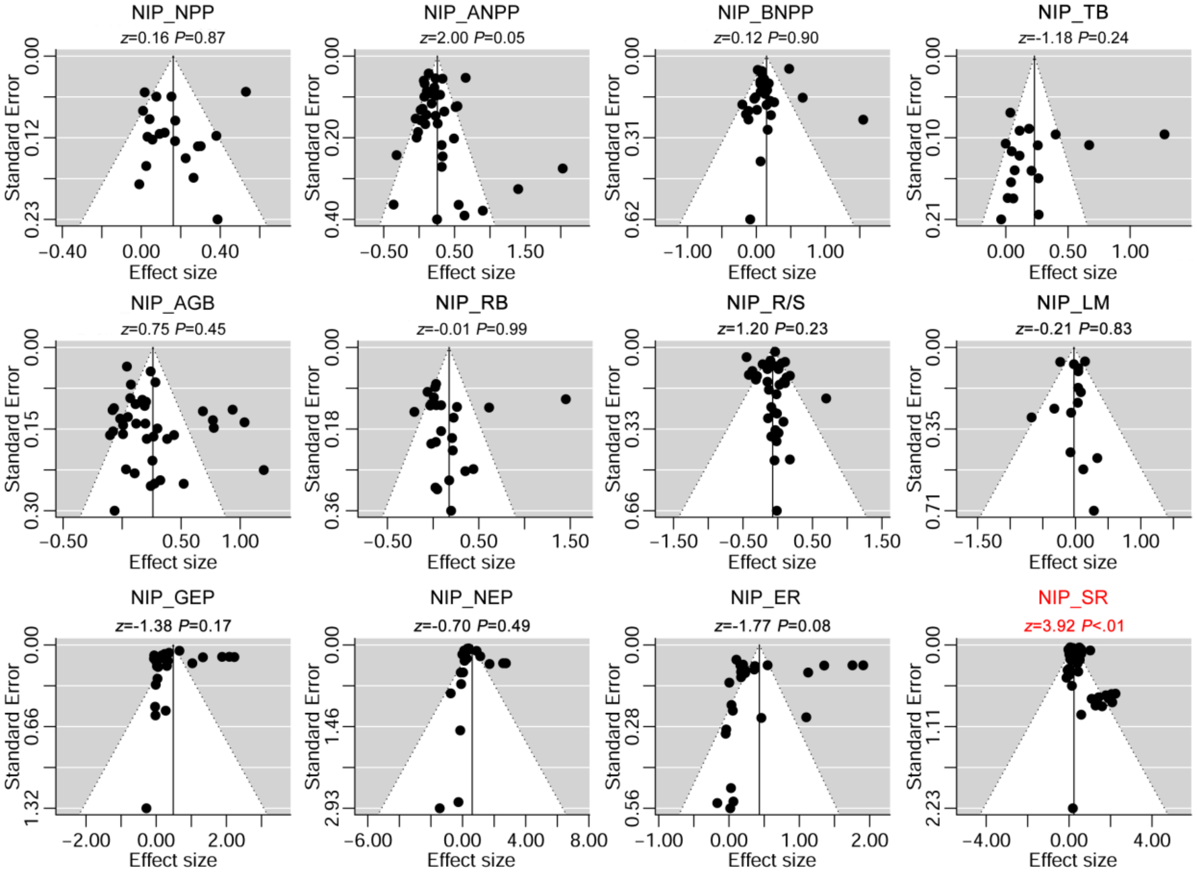

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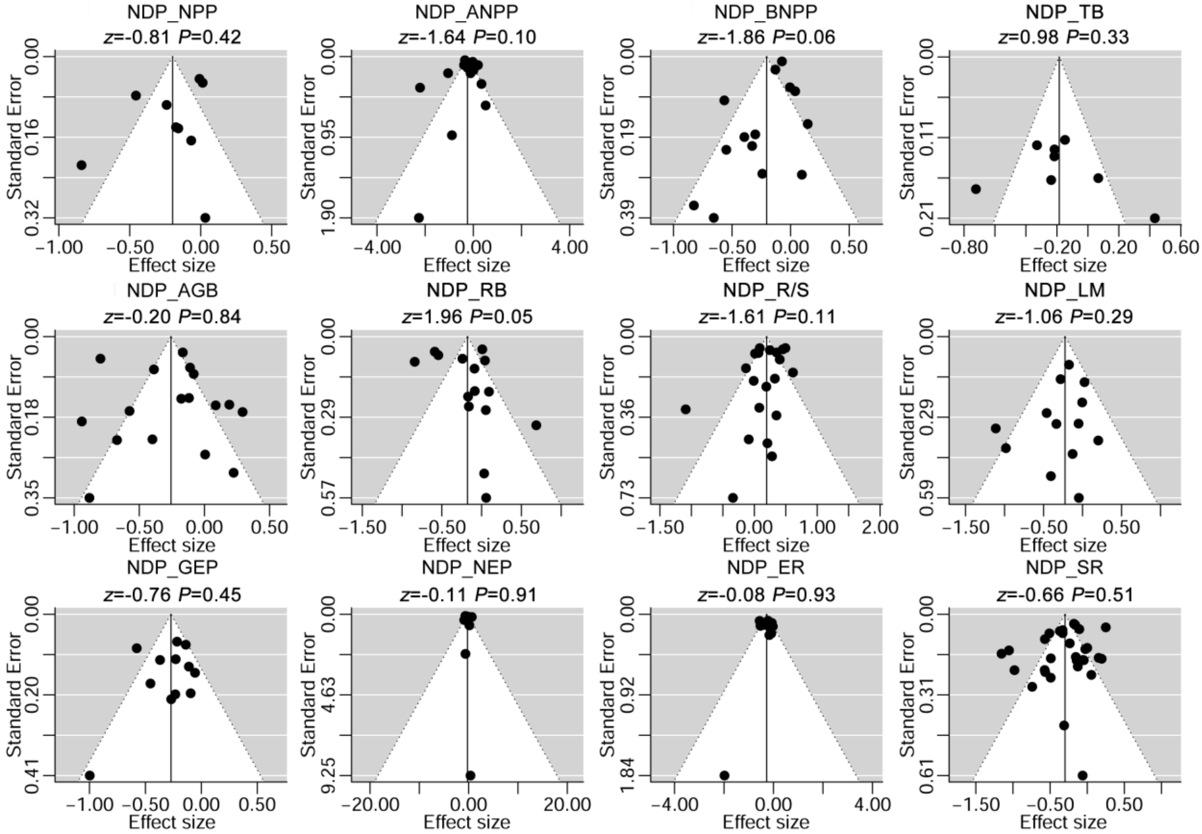
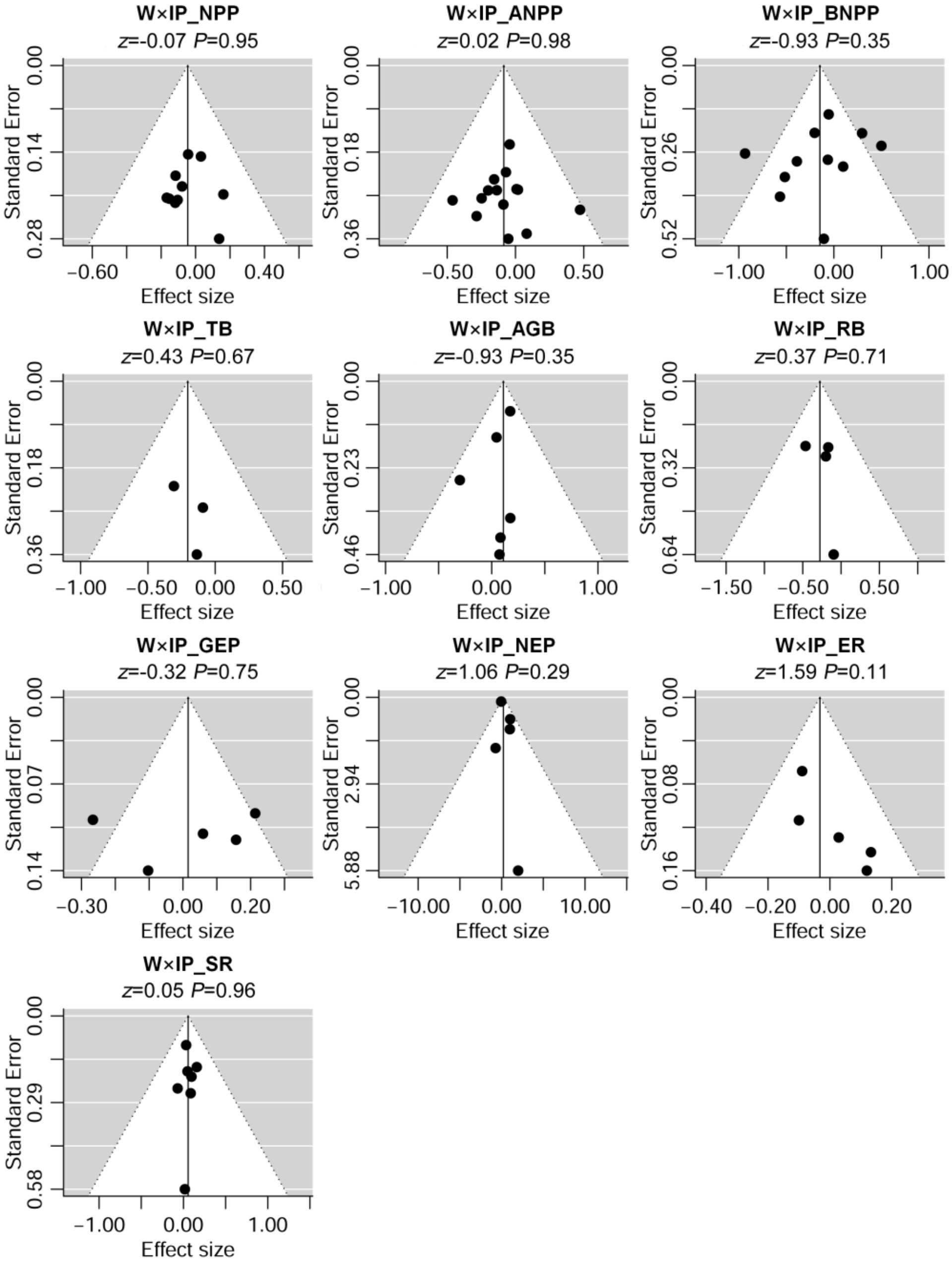


Supplementary Figure 15. Assessments of publication bias. Funnel plots of ecosystem carbon-cycle variables under the interaction between W and IP treatments (W×IP). Results of publication bias tests using Egger's regression are given at the top of each panel (*z* and *P* values). *P* values > 0.05 indicate the absence of publication bias. See Supplementary Figures 2 and 3 for variable abbreviations.



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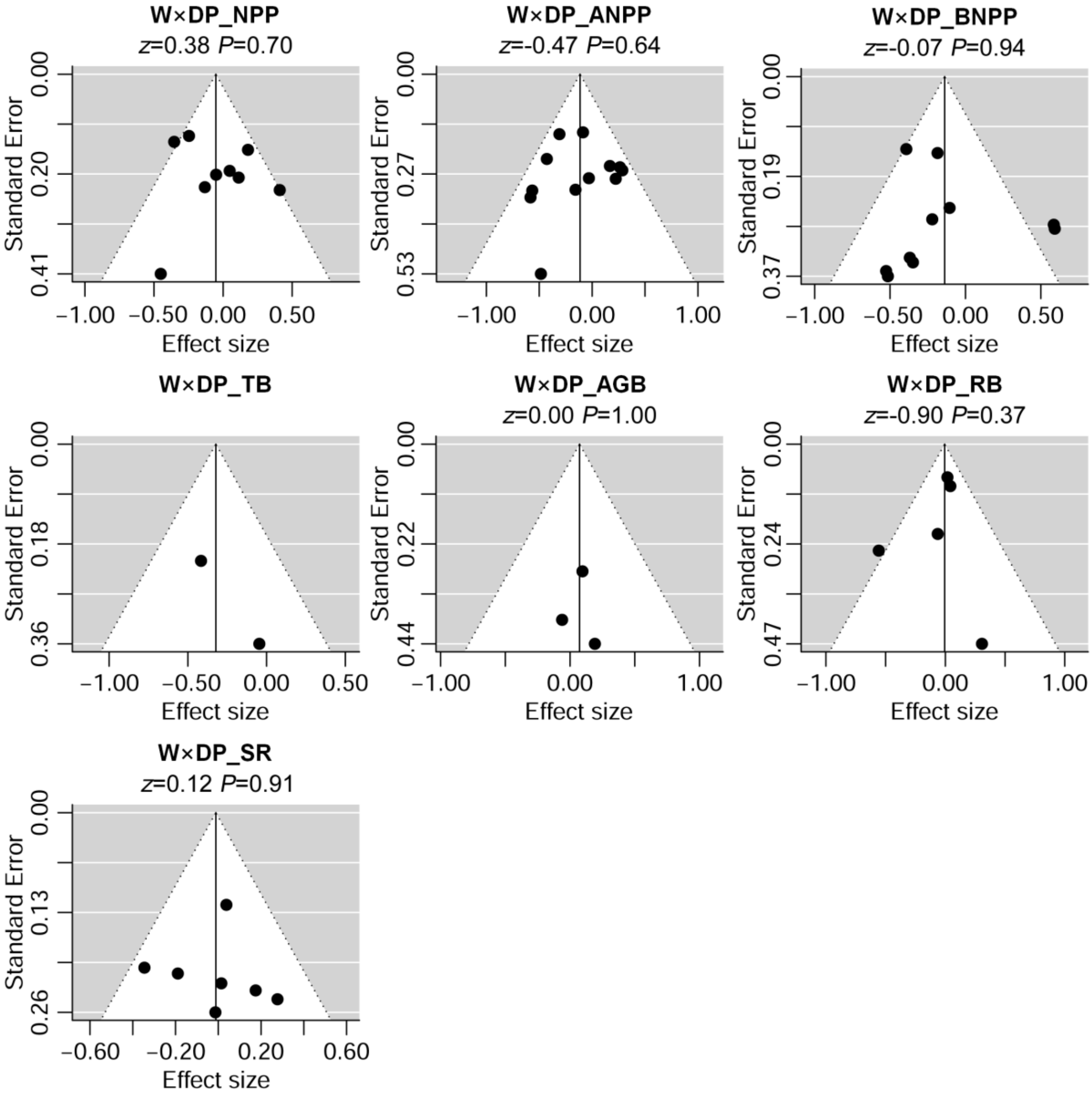
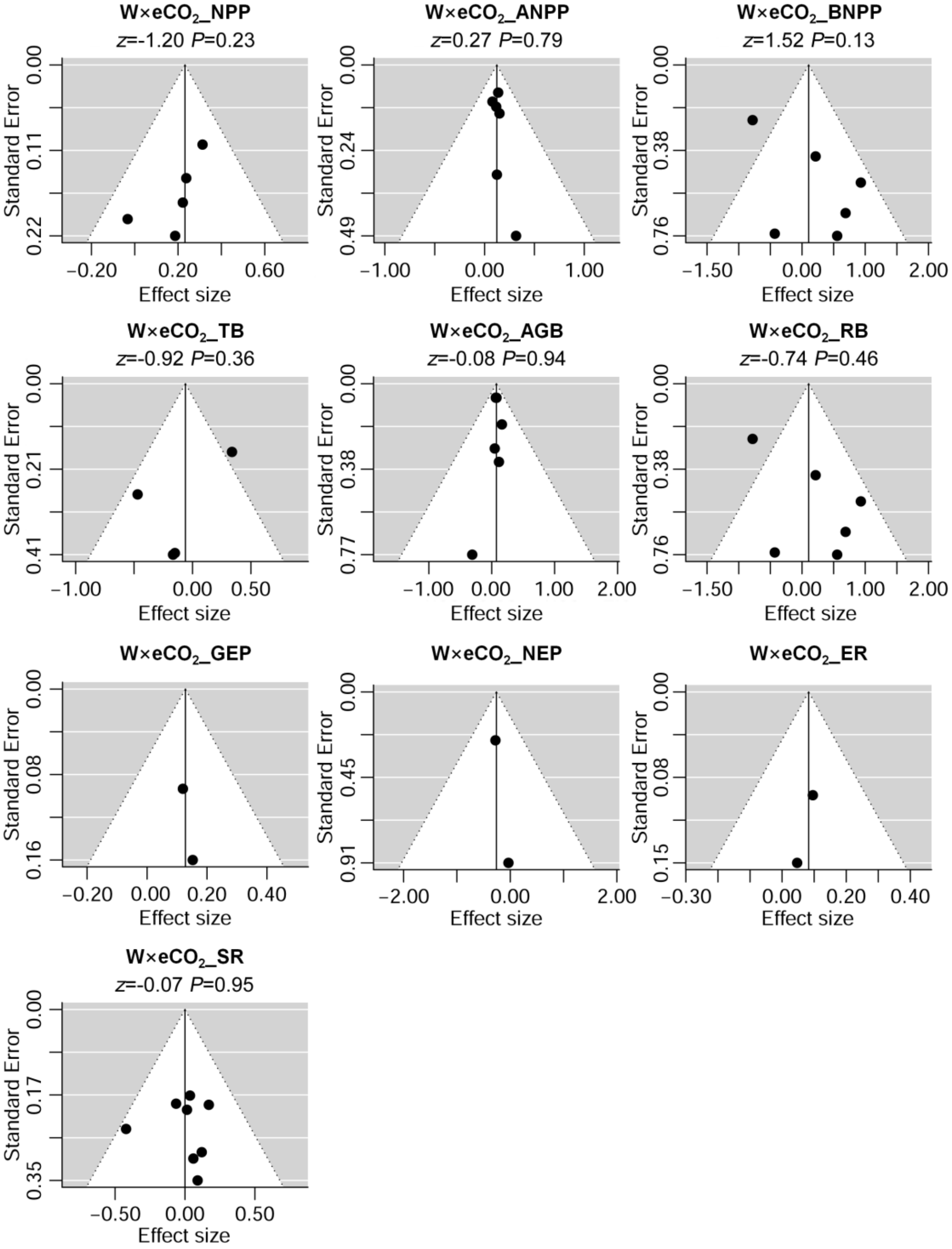


Supplementary Figure 17. Assessments of publication bias. Funnel plots of ecosystem carbon-cycle variables under the interaction between W and eCO_2 treatments ($W \times eCO_2$). Results of publication bias tests using Egger's regression are given at the top of each panel (*z* and *P* values). *P* values > 0.05 indicate the absence of publication bias. See Supplementary Figures 2 and 3 for variable abbreviations.



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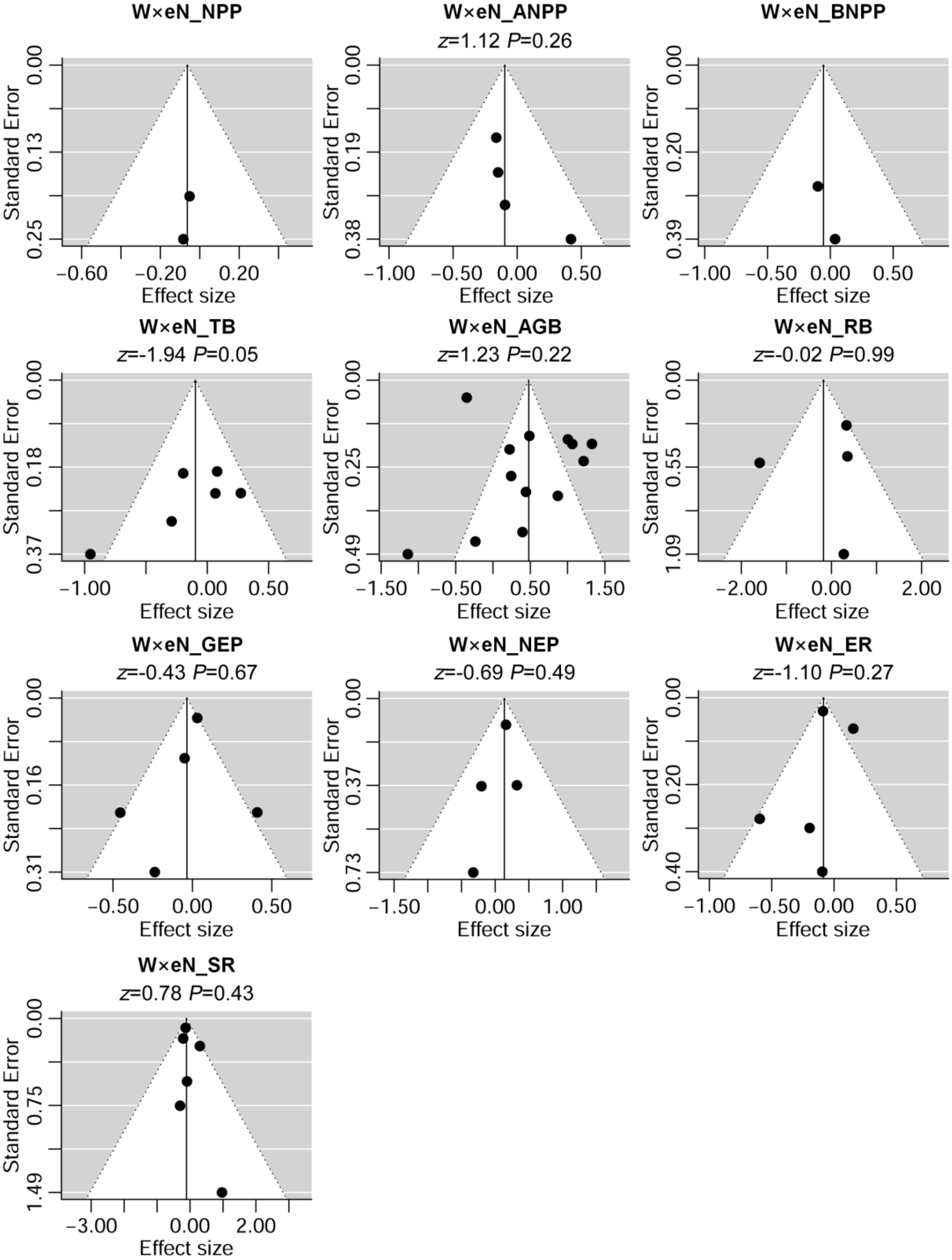
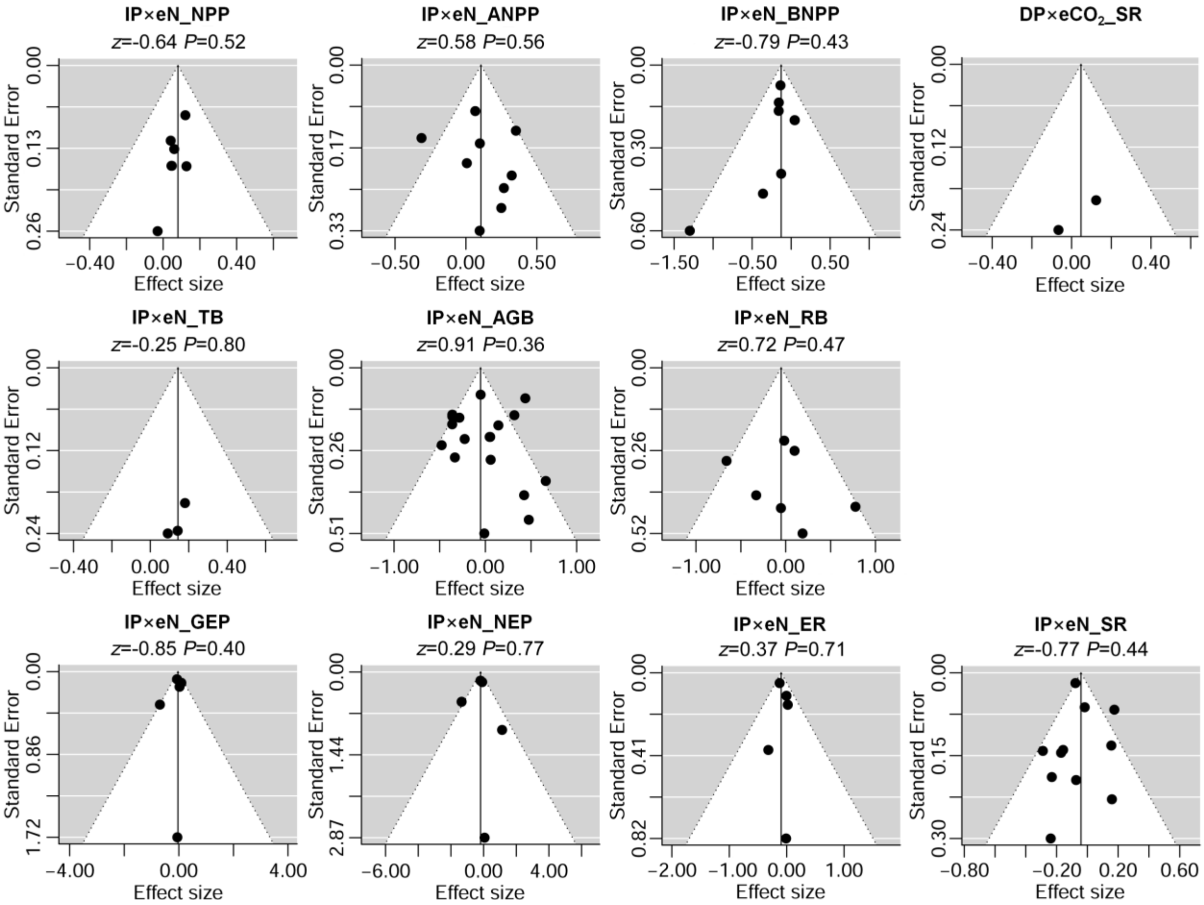
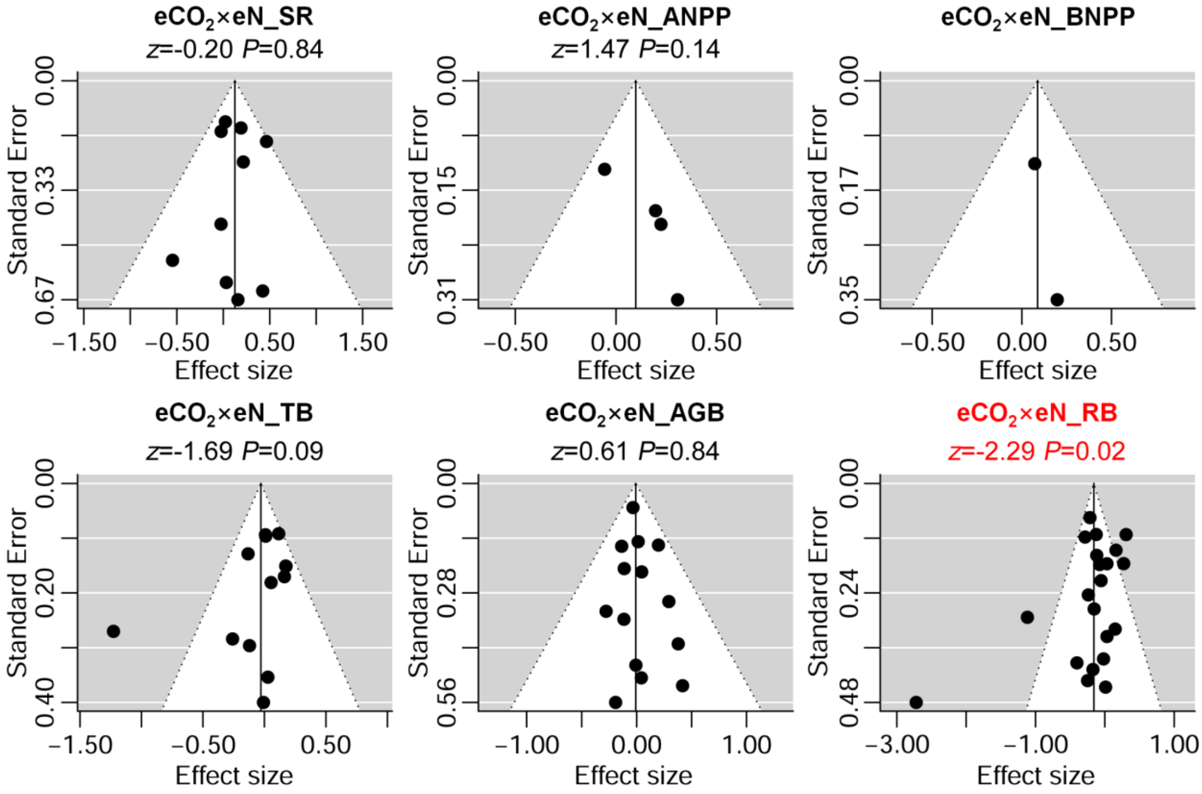


Supplementary Figure 19. Assessments of publication bias. Funnel plots of ecosystem carbon-cycle variables under the interaction between IP and eN treatments (IP×eN) and between DP and eCO_2 treatments (DP×eCO_2). Results of publication bias tests using Egger's regression are given at the top of each panel (*z* and *P* values). *P* values > 0.05 indicate the absence of publication bias. See Supplementary Figures 2 and 3 for variable abbreviations.



Supplementary Figure 20. Assessments of publication bias. Funnel plots of ecosystem carbon-cycle variables under the interaction between eCO_2 and eN treatments (eCO_2×eN). Results of publication bias tests using Egger's regression are given at the top of each panel (*z* and *P* values). *P* values > 0.05 indicate the absence of publication bias. See Supplementary Figures 2 and 3 for variable abbreviations.



Supplementary Table 1. The number of experiments manipulating single and multiple global change drivers in different countries.

Continent	Country	W	P	eCO$_2$	eN	WP	WeCO$_2$	WeN	PeCO$_2$	PeN	eCO$_2$eN	WPeCO$_2$	WPeN	WeCO$_2$eN	PeCO$_2$eN	WPeCO$_2$eN
Europe	UK	6	5	10	24	1	-	1	1	1	6	-	-	-	-	-
	SE	8	3	4	40	-	2	4	-	3	3	-	1	-	1	-
	SL	2	7	9	41	2	2	4	-	2	7	-	-	-	-	-
	NL	1	1	4	21	-	-	-	-	1	1	-	-	-	-	-
	RU	18	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	SP	4	10	1	4	3	-	-	-	1	-	-	-	-	-	-
	GE	1	7	3	12	2	-	-	-	2	1	-	-	-	-	-
	IT	3	2	5	5	-	-	-	-	1	1	-	-	-	-	-
	FR	3	5	3	1	2	1	-	-	1	-	1	-	-	-	-
	NO	13	2	-	5	1	1	1	-	1	-	-	1	-	-	-
	DK	1	2	-	2	-	-	-	-	-	-	1	-	-	-	-
	FI	1	-	4	8	-	1	-	-	2	-	-	-	1	-	-
	IS	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	IE	-	1	1	-	-	-	-	-	-	1	-	-	-	-	-
	BE	1	-	1	-	1	1	1	-	-	-	1	-	1	-	-
	CZ	1	2	1	3	-	-	-	-	-	-	-	-	-	-	-
	EE	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	HU	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
	AT	1	1	-	-	1	-	-	-	-	-	-	-	-	-	-
	PL	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
	GR	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	PT	-	1	-	1	-	-	-	-	1	-	-	-	-	-	-
Asia	CN	23	20	7	91	12	3	10	3	30	3	-	-	-	-	1
	JP	6	2	3	1	-	1	-	-	-	-	-	-	-	-	-
	ID	-	3	-	1	-	-	-	-	-	-	-	-	-	-	-
	IN	-	-	1	3	-	-	-	-	1	-	-	-	-	-	-
	KR	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	IL	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-
	MN	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
North America	US	35	64	34	115	28	5	6	1	22	19	4	1	-	3	1
	CA	16	2	4	21	6	1	5	-	1	-	-	1	-	-	-
	PA	-	1	2	3	-	-	-	-	-	1	-	-	-	-	-
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	JM	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
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South America	BR	-	5	-	7	-	-	-	-	8	-	-	-	-	-	-
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	AR	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-
	EC	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
	PE	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Oceanica	AU	1	2	3	3	-	3	-	1	1	-	-	-	-	-	-
	NZ	3	1	3	2	3	-	1	-	-	1	-	-	-	-	-
Africa	ZA	2	2	-	1	-	-	-	-	1	-	-	-	-	-	-
Antarctica		2	-	-	-	-	-	-	-	1	-	-	1	-	-	-

Key to treatment abbreviations: W: warming, P: changing precipitation regimes, eCO$_2$: elevated CO$_2$, eN: enriched atmospheric nitrogen deposition, treatments in multifactor experiments are shown with multiple letters.

Country abbreviations: UK: United Kingdom, SE: Sweden, SL: Switzerland, NL: The Netherlands, RU: Russia, SP: Spain, GE: Germany, IT: Italy, FR: France, NO: Norway, DK: Denmark, FI: Finland, IS: Iceland, IE: Ireland, BE: Belgium, CZ: Czech Republic, EE: Estonia, HU: Hungary, AT: Austria, The Republic of Greece: GR, PT: Portugal, PL: Poland, CN: China, JP: Japan, ID: Indonesia, IN: India, KR: Korea, IL: Israel, MN: Mongolia, US: United States of America, CA: Canada, PA: Panama, MX: Mexico, JM: Jamaica, BZ: Belize, BR: Brazil, CL: Chile, AR: Argentina, EC: Ecuador, PE: The Republic of Peru, AU: Australia, NZ: New Zealand, ZA: South African.

Supplementary Table 2. The numbers of samples and experiments (shown in parentheses) collected in our meta-analysis (all available data).

	NPP	ANPP	BNPP	TB	AGB	RB	R/S	LM	GEP	NEP	ER	SR	pH
W	43(8)	82(21)	55(10)	34(21)	108(53)	46(27)	45(24)	42(15)	82(24)	80(23)	91(26)	124(40)	–
IP	43(18)	93(27)	64(23)	38(12)	83(32)	41(18)	49(28)	30(10)	67(21)	66(20)	69(22)	105(40)	–
DP	24(9)	44(16)	35(10)	14(5)	28(13)	22(10)	28(14)	37(9)	29(10)	29(10)	29(10)	59(26)	–
eCO$_2$	39(7)	25(10)	51(12)	66(33)	237(59)	171(63)	43(27)	35(16)	23(6)	58(10)	17(8)	110(31)	–
eN	30(10)	82(27)	45(15)	50(22)	357(99)	120(51)	68(39)	40(15)	35(10)	34(11)	39(11)	188(45)	89(53)
WIP	22(6)	28(8)	28(7)	9(3)	14(6)	12(5)	–	–	25(5)	25(5)	25(5)	27(7)	–
WDP	17(5)	24(7)	18(7)	3(3)	10(5)	6(5)	–	–	–	–	–	19(7)	–
WeCO$_2$	9(2)	10(3)	10(3)	8(4)	18(6)	11(5)	–	–	9(2)	9(2)	9(2)	22(7)	–
WeN	10(2)	12(4)	10(2)	10(5)	20(9)	10(3)	–	–	13(4)	13(4)	13(4)	18(6)	–
IPeCO$_2$	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–
DPeCO$_2$	–	–	–	–	–	–	–	–	–	–	–	6(2)	–
IPeN	15(6)	23(7)	20(7)	15(3)	57(13)	20(6)	–	–	20(5)	20(5)	20(5)	26(7)	–
eCO$_2$eN	5(1)	8(2)	7(2)	24(10)	24(10)	29(14)	–	–	–	–	–	22(7)	–
WIPeCO$_2$	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–
WIPeN	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–
WDPeCO$_2$	–	–	–	–	–	–	–	–	–	–	–	6(2)	–
WeCO$_2$eN	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–
IPeCO$_2$eN	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–
WIPeCO$_2$eN	5(1)	5(1)	5(1)	–	–	–	–	–	–	–	–	–	–

See Supplementary Table 1 and Supplementary Figures. 2 and 3 for treatment and variable abbreviations, respectively. IP: increased precipitation, DP: decreased precipitation.

Supplementary Table 3. The numbers of samples and experiments (shown in parentheses) used in our meta-analysis after independent checking (see Methods for details).

	NPP	ANPP	BNPP	TB	AGB	RB	R/S	LM	GEP	NEP	ER	SR	pH
W	18(8)	37(21)	20(10)	26(21)	64(53)	33(27)	36(24)	20(15)	34(24)	31(23)	37(26)	51(40)	–
IP	22(18)	41(27)	31(23)	18(12)	40(32)	24(18)	36(28)	15(10)	26(21)	25(20)	27(22)	57(40)	–
DP	11(9)	23(16)	16(10)	8(5)	17(13)	15(10)	22(14)	14(9)	12(10)	12(10)	12(10)	31(26)	–
eCO$_2$	10(8)	13(10)	19(12)	51(33)	99(57)	96(61)	40(27)	25(16)	8(6)	12(10)	9(9)	48(31)	–
eN	12(10)	39(27)	17(15)	33(22)	201(99)	90(52)	65(39)	31(15)	13(10)	15(11)	16(11)	91(45)	89(53)
WIP	10(6)	14(8)	10(7)	3(3)	6(6)	5(5)	–	–	5(5)	5(5)	5(5)	7(7)	–
WDP	9(5)	13(7)	10(7)	3(3)	5(5)	6(5)	–	–	–	–	–	7(7)	–
WeCO$_2$	5(2)	6(3)	6(3)	4(4)	7(6)	5(5)	–	–	2(2)	2(2)	2(2)	8(7)	–
WeN	2(2)	4(4)	2(2)	6(5)	13(9)	4(3)	–	–	5(4)	4(4)	5(4)	6(6)	–
IPeCO$_2$	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–
DPeCO$_2$	–	–	–	–	–	–	–	–	–	–	–	2(2)	–
IPeN	7(6)	9(7)	8(7)	3(3)	19(13)	8(6)	–	–	5(5)	5(5)	5(5)	14(7)	–
eCO$_2$eN	1(1)	4(2)	2(2)	13(10)	14(10)	22(14)	–	–	–	–	–	10(7)	–
WIPeCO$_2$	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–
WIPeN	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–
WDPeCO$_2$	–	–	–	–	–	–	–	–	–	–	–	2(2)	–
WeCO$_2$eN	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–
IPeCO$_2$eN	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–
WIPeCO$_2$eN	1(1)	1(1)	1(1)	–	–	–	–	–	–	–	–	–	–

See Supplementary Table 1 and Supplementary Figures. 2 and 3 for treatment and variable abbreviations, respectively. IP: increased precipitation, DP: decreased precipitation.

Supplementary Table 4. The numbers of samples and experiments (shown in parentheses) used in the interaction calculations.

	NPP	ANPP	BNPP	TB	AGB	RB	GEP	NEP	ER	SR
W×IP	10(6)	14(8)	10(7)	3(3)	6(6)	4(4)	5(5)	5(5)	5(5)	7(7)
W×DP	9(5)	12(6)	10(7)	2(2)	3(3)	5(4)	–	–	–	7(7)
W×eCO$_2$	5(2)	6(3)	6(3)	4(4)	6(5)	5(5)	2(2)	2(2)	2(2)	8(7)
W×eN	2(2)	4(4)	2(2)	6(5)	13(9)	4(3)	5(4)	5(4)	5(4)	6(6)
IP×eN	7(6)	9(7)	8(7)	3(3)	19(13)	7(5)	5(5)	5(5)	5(5)	12(6)
DP×eCO$_2$	–	–	–	–	–	–	–	–	–	2(2)
eCO$_2$×eN	–	4(2)	2(2)	13(10)	14(10)	22(14)	–	–	–	10(7)

See Supplementary Table 1 and Supplementary Figures. 2 and 3 for treatment and variable abbreviations, respectively. IP: increased precipitation, DP: decreased precipitation.

Supplementary Text 1: List of 2230 publications of manipulative experiments in global change research used in this synthesis.

1970-1989

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Supplementary Text 2: Discussion on the discrepancy between our findings and those from previous meta-analyses.

Discrepancy between our findings and those from previous meta-analyses: Effects of individual global change drivers

Warming effects

Our meta-analysis results showed that warming did not affect net primary productivity and its aboveground component, root-to-shoot ratios, litter mass, gross and net ecosystem productivity, or ecosystem respiration. However, warming marginally increased belowground net primary productivity by 18.6% ($P = 0.066$). In addition, warming significantly stimulated total, aboveground, and root biomass, and soil respiration by 23.2%, 13.7%, 13.5%, and 14.1%, respectively (all $P < 0.05$). These observations of neutral responses of plant productivity to warming are inconsistent with the findings of several previous meta-analyses, which have demonstrated significant increases in net primary productivity ranging from 4.4% to 19.0% (Rustad et al., 2001; Wu et al., 2011; Lu et al., 2013), and a greater belowground net primary productivity enhancement (+52%; Wu et al., 2011). Our meta-analysis results of significant stimulations in plant biomass are in line with the observations of a previous meta-analysis showing a plant biomass increase of 12.3% under elevated temperature (Lin et al., 2010). However, another meta-analysis has found that warming could only stimulate aboveground biomass by 27%, but has no effect on total or root biomass (Wu et al., 2011).

Our findings of neutral responses of gross ecosystem productivity and ecosystem respiration to warming are disagreement with the observations of two previous meta-analyses, which have demonstrated significant increases of gross ecosystem productivity ranging from 15.7% to 20.0%, and an enhancement of 27% for ecosystem respiration (Wu et al., 2011; Lu et al., 2013). However, net ecosystem productivity, the balance between gross ecosystem productivity and ecosystem respiration, showing no response to warming detected in our study is in consistent with the findings of two previous meta-analyses (Wu et al., 2011; Lu et al., 2013). In addition, a 13.2% increase of soil respiration in response to warming revealed in our study is also within the range of previous observations (+12%~+20%; Rustad et al., 2001; Wu et al., 2011; Wang et al., 2014).

Effects of increased/decreased precipitation

Our meta-analysis results found that increased precipitation significantly stimulated most of the carbon-cycle variables, including net primary productivity (+28.0%) and its above- (+37.3%) and below-ground components (+19.4%), total (+13.7%), aboveground (+20.3%), and root biomass (+14.8%), gross (+28.8%) and net ecosystem productivity (+35.6%), as well as ecosystem (+28.0%) and soil respiration (+21.9%), but reduced root-to-shoot ratios by 11.4%. However, increased precipitation did not influence litter mass. These findings are similar to the observations of a previous meta-analysis, which has found that increased precipitation could significantly stimulate net primary productivity (+4%) and its above- (+28%) and below-ground components (+6%), aboveground (+12%) and root biomass (+11%), gross (+40%) and net ecosystem productivity (+56%), as well as ecosystem (+30%) and soil respiration (+45%), but do not affect total biomass (Wu et al., 2011). In addition, another recent meta-analysis has revealed that normalized increased precipitation (a 28% precipitation increase) could enhance soil respiration by 16% (Liu et al., 2016).

Our meta-analysis results demonstrated that decreased precipitation suppressed all the carbon-cycle variables, including net primary productivity (-14.7%) and its above- (-19.0%) and below-ground components (-14.5%), total (-17.7%), aboveground (-16.3%), and root biomass (-15.6%), litter mass (-19.5%), gross (-24.8%) and net ecosystem productivity (-27.4%), as well as ecosystem (-24.7%) and soil respiration (-23.0%), but stimulated root-to-shoot ratios by 17.9%. However, a previous meta-analysis has found an inconsistent pattern of carbon-cycle variable responses to decreased precipitation that decreased precipitation could reduce aboveground net primary productivity (-37%), aboveground biomass (-15%), gross (-9%) and net ecosystem productivity (-45%), and soil respiration (-12%), but do not affect total and root biomass, net primary productivity and its belowground component, or ecosystem respiration (Wu et al., 2011). Another recent meta-analysis has demonstrated that normalized decreased precipitation (a 28% precipitation decrease) could suppress soil respiration by 17% (Liu et al., 2016).

Effects of elevated CO_2

Our meta-analysis results found that elevated CO_2 (eCO_2) significantly increased most of the carbon-cycle variables, including net primary productivity (+14.3%) and its above- (+17.9%) and below-ground components (+35.4%), total (+24.4%), aboveground (+17.2%), and root biomass (+28.6%), root-to-shoot ratios (+14.9%), and ecosystem (+15.0%) and soil respiration (+30.4%), but did not affect gross or net ecosystem productivity. However, several previous meta-analyses have primarily focused on the responses of plant biomass production to rising atmospheric CO_2, but fewer studies examining the eCO_2 effects on the other carbon-cycle variables. These meta-analyses have demonstrated that eCO_2 could stimulate total (+28.8%~+44.0%; Curtis & Wang, 1998; Wand et al., 1999), aboveground (+20%; Ainsworth & Long 2005; Sillen & Dieleman, 2012), and root biomass (+28.8%~+38.0%; Curtis & Wang, 1998; Nie et al., 2013). However, a previous meta-analysis has reported a negative root biomass response to eCO_2 (-17.0%; Sillen & Dieleman, 2012). In addition, compared with our observations, the previous meta-analyses have revealed a lower positive response of root-to-shoot ratios to eCO_2 (+6.7%~+8.5%; Luo et al., 2006; Nie et al., 2013).

Effects of nitrogen (N) addition

Our meta-analysis results showed that N addition significantly stimulated most of the carbon-cycle variables, including net primary productivity (+16.3%) and its aboveground component (+13.4%), total (+55.7%), aboveground (+30.8%), and root biomass (+20.1%), litter mass (+27.7%), gross ecosystem productivity (+37.8%), and ecosystem respiration (+36.5%), but reduced root-to-shoot ratios and soil respiration by 16.8% and 4.8%, respectively. However, N addition did not influence belowground net primary productivity or net ecosystem productivity. Several previous meta-analyses have only focused on plant biomass responses to N addition, revealing a lower stimulation in total biomass under N addition ranging from 36% (Janssens et al., 2010) to 53.6% (Xia & Wan, 2008), and greater enchantments of aboveground (37%) and root biomass (29%; Sillen & Dieleman, 2012) than those detected in our study. In addition, a previous meta-analysis focusing on forested ecosystems have demonstrated a higher reduction in soil respiration (-10%) under N addition than results observed in our study (Janssens et al., 2010), suggesting that including other ecosystems such as grasslands and tundra generates a lower negative impact of N addition on soil respiration.

Overall, since these meta-analyses including ours generally used the same methods (weighted log-response ratios) performed with various software (e.g., MetaWin or 'Metafor' package in R), the different findings among studies were generated primarily due to that these studies represented different experiments in the analyses. Our study encompassing all global change manipulative experiments to 2016 can provide a large and valuable database for global change research to facilitate our understanding of ecosystem carbon-cycle responses to global change drivers.

Discrepancy between our findings and those from previous meta-analyses: Interactive effects

During the past two decades, there were fewer meta-analyses to examine the interactive effects among multiple global change drivers (e.g., Dieleman et al., 2012; Zhou et al., 2016; Yue et al., 2017), likely due to fewer multifactor experiments precluding the identification of interactive effects. The discrepancy in the findings among the previous meta-analyses has been discussed in a previous study (Yue et al., 2017). Briefly, Dieleman et al. (2012) has revealed antagonistic effects between eCO_2 and warming on plant biomass and soil process variables (e.g., soil respiration, soil carbon content, and net N mineralization). However, Zhou et al. (2016) and Yue et al. (2017) have suggested that nonlinear influences (i.e. synergistic or antagonistic) between two-driver pair were rare. Yue et al. (2017) argued that the differences in analytical methods and the variables analyzed in each study could be responsible for the discrepancy. For example, Dieleman et al. (2012) assessed interactions between warming and eCO_2 on plant biomass and soil process variables (e.g., soil respiration, soil carbon content, and net N mineralization) by comparing the linear correlations between the combined warming and eCO_2 influences and the sum of individual effects with 1:1 line. Leuzinger et al. (2011) pooled plant biomass and soil process variables together to explore the differences in the response magnitudes under one, two, and three global change drivers.

Compared with Zhou et al. (2016) and Yue et al. (2017) which used Hedges' *d* method, our study used a different method, but generated similar findings of more multiplicative influences. In addition, another recent meta-analysis has found that eCO_2 and warming could multiplicatively affect aboveground biomass of woody plants, providing other lines of evidence to support our observations (Baig et al., 2015). Furthermore, given that a previous analysis has pooled multiple carbon-cycle variables together to analyze effects of multiple global change drivers, and found that ecosystem responses decline with increasing number of global change drivers (Leuzinger et al., 2011). From a global perspective, more direct evidence on whether multiplicative effects among higher-order global change drivers hold for experimental studies manipulating three or four drivers are crucial for robust projections of future global change-terrestrial carbon cycling feedbacks.

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