

Supplementary Material

Title: Warming and increased precipitation synergy undermines soil multifunctionality through enhanced bacterial–fungal competition in semiarid grasslands

Running title: Enhanced microbial competition undermines soil multifunctionality

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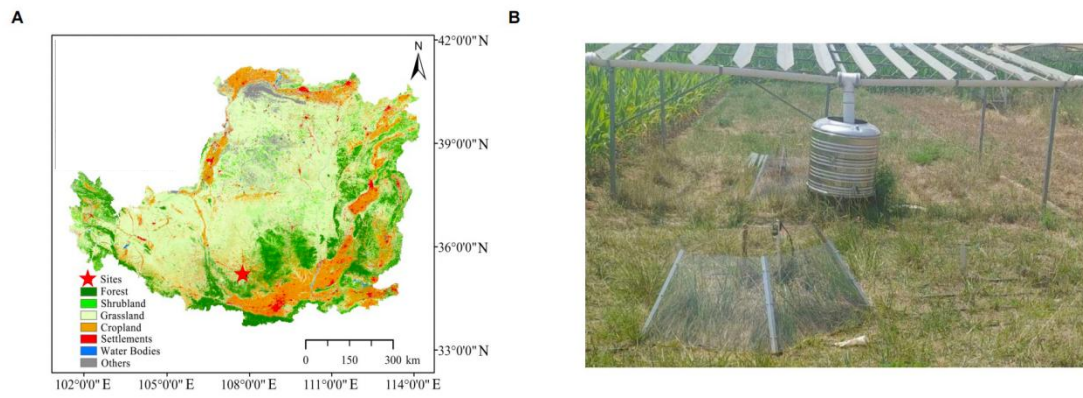


Figure S1 Location of the study area in the Loess Plateau, China (A) and simulation experiment diagram of warming and precipitation change (B).

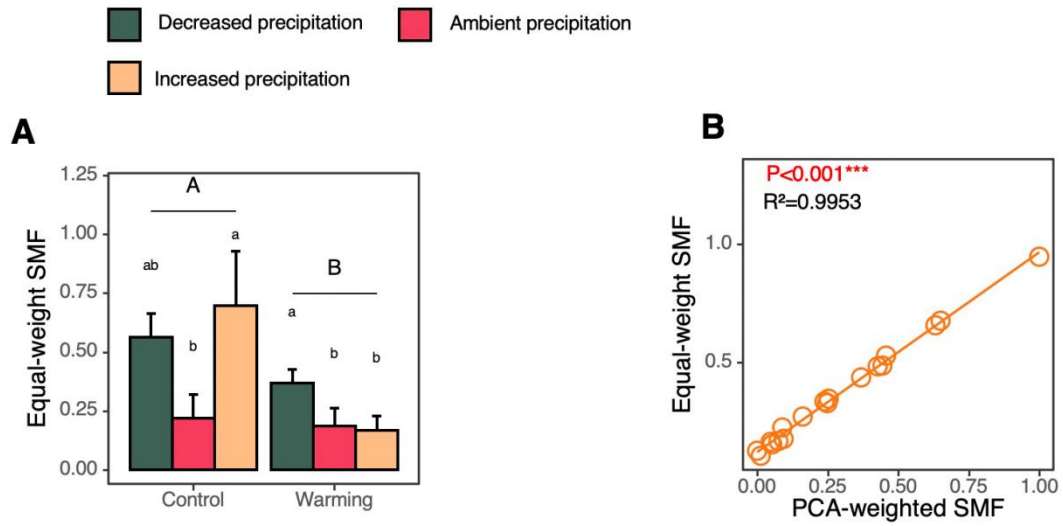


Figure S2 (A) Equal-weight SMF under warming and precipitation changes. (B) The linear relationship between equal-weight SMF and PCA-weighted SMF. Lowercase letters indicate significant differences (Tukey's post hoc test, HSD) between different precipitation levels. Capital letters indicate significant differences

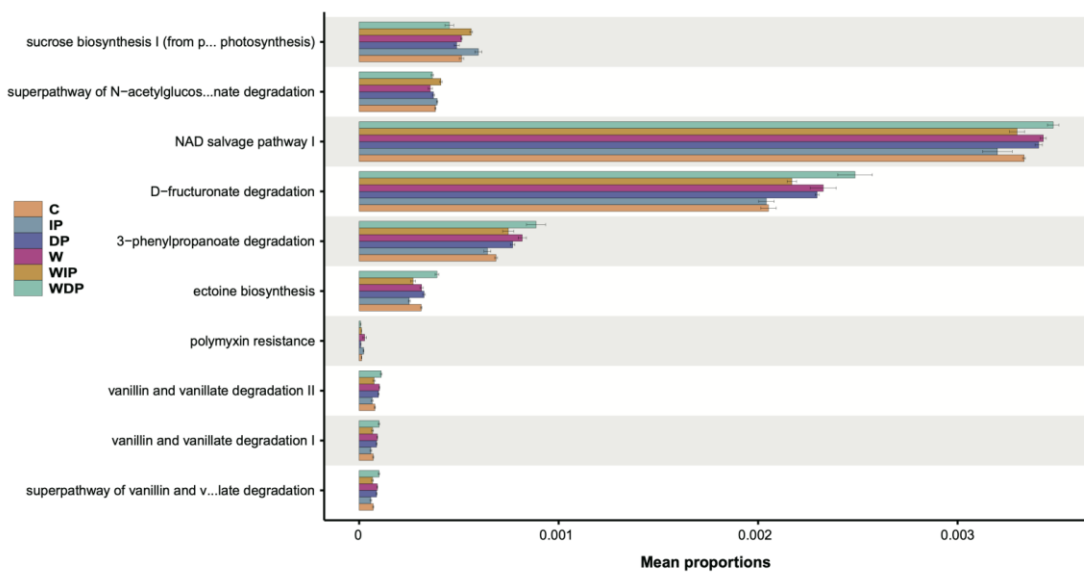


Figure S3 Differential Abundance of PICRUSt2-Predicted Pathways under warming and precipitation changes. Treatments: C: control, DP: decreased precipitation, IP: increased precipitation, W: warming, WDP: warming with decreased precipitation, WIP: warming with increased precipitation.

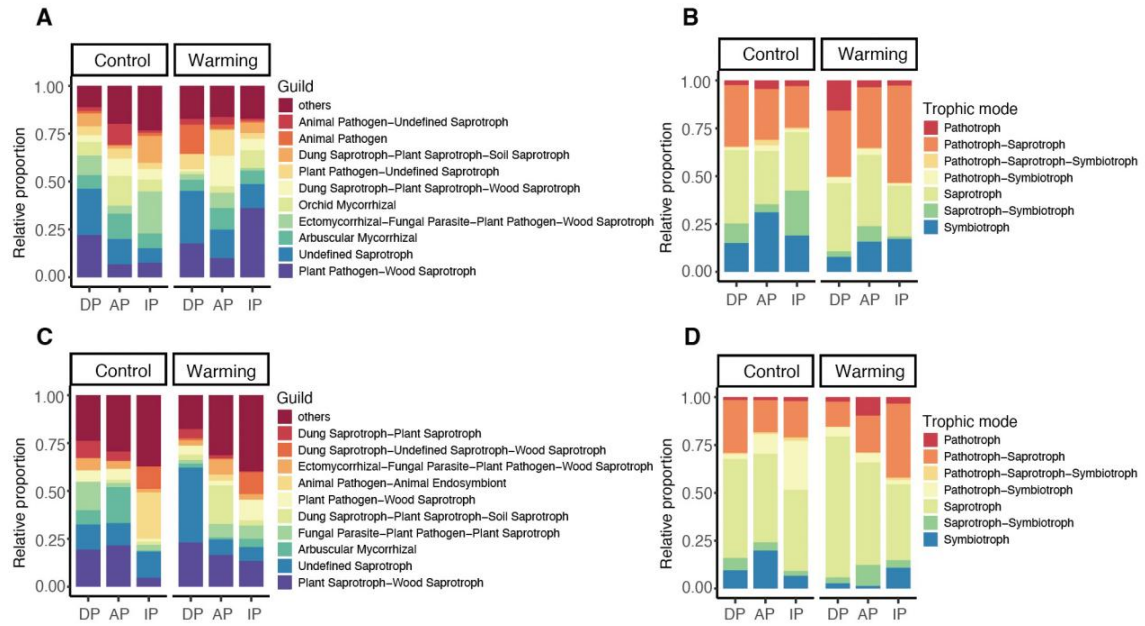


Figure S4 Variations in composition of fungal functional groups (guilds) (A; C) and trophic mode (B; D) inferred by FUNGuild.

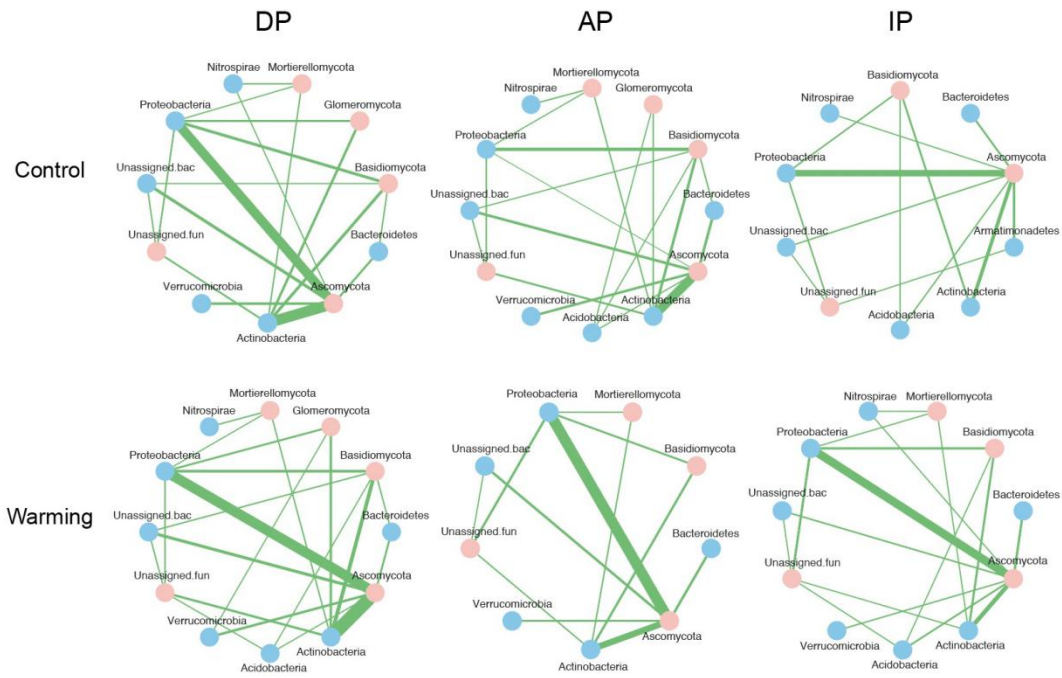


Figure S5 Microbial networks under warming and precipitation changes. The size of nodes indicates the relative abundance of species (at genus level). Blue and red nodes indicate the classification of bacteria and fungi at the phylum level, respectively. The width of the edges indicates the strength of the connection between species.

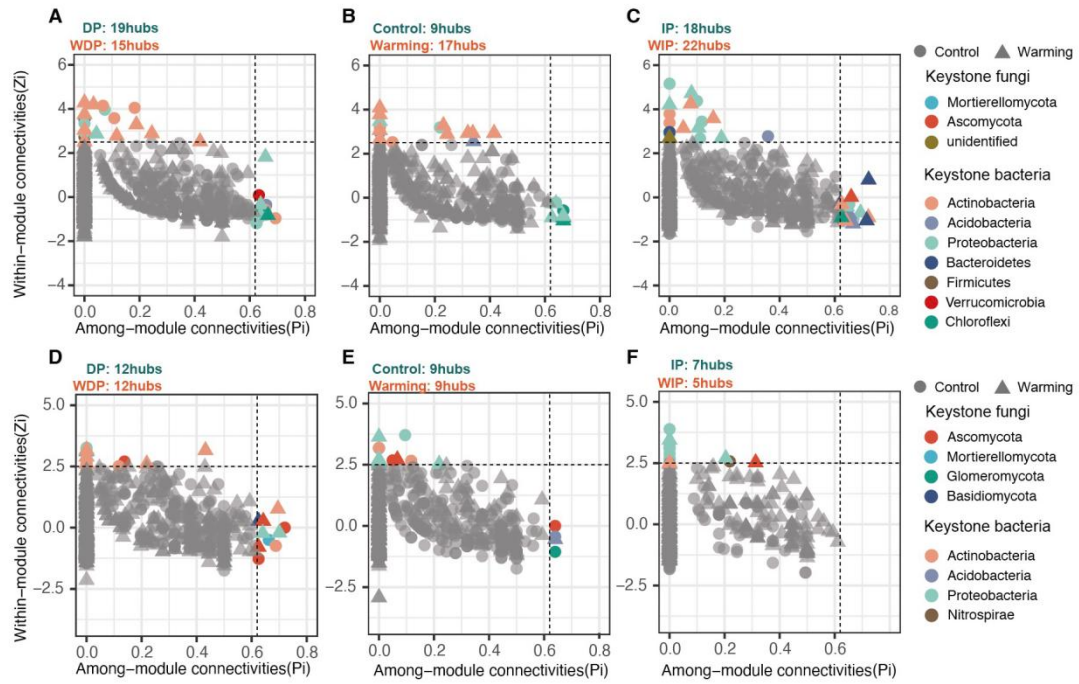


Figure S6 The keystones of co-occurrence networks under decreased precipitation (A), controlled precipitation (B) and increased precipitation (C).

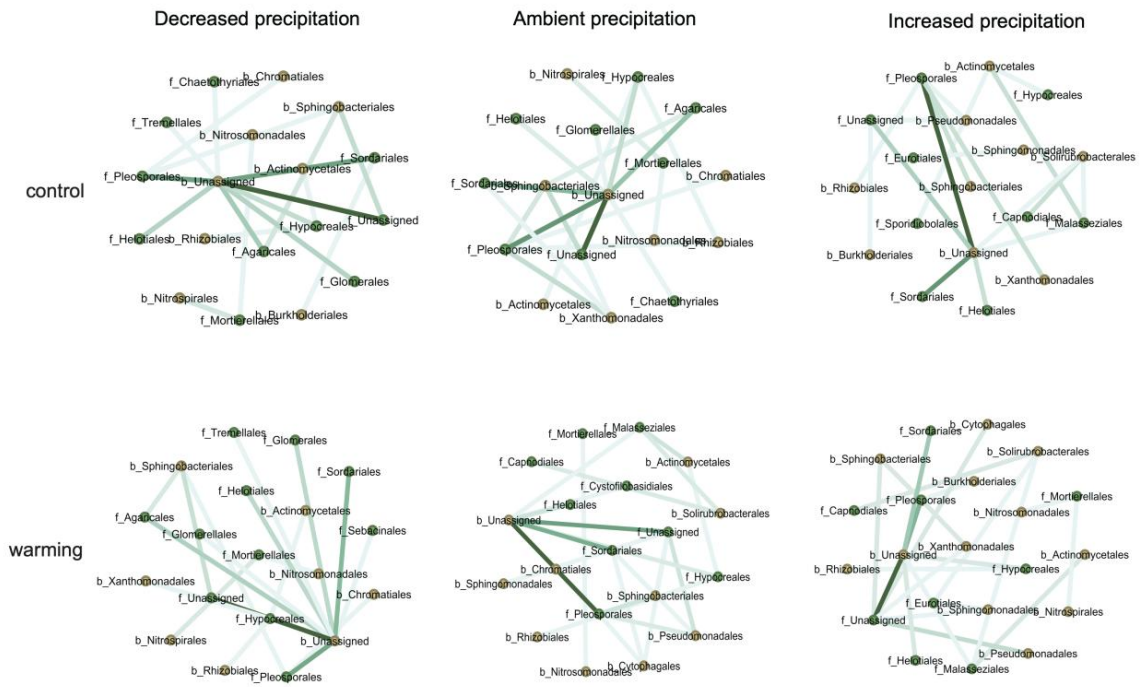


Figure S7 Negative bacterial-fungal interactions under under warming and precipitation changes. Yellow and green nodes represent bacterial and fungal taxa at the order level, respectively. Edge width indicates the number of connections between species.

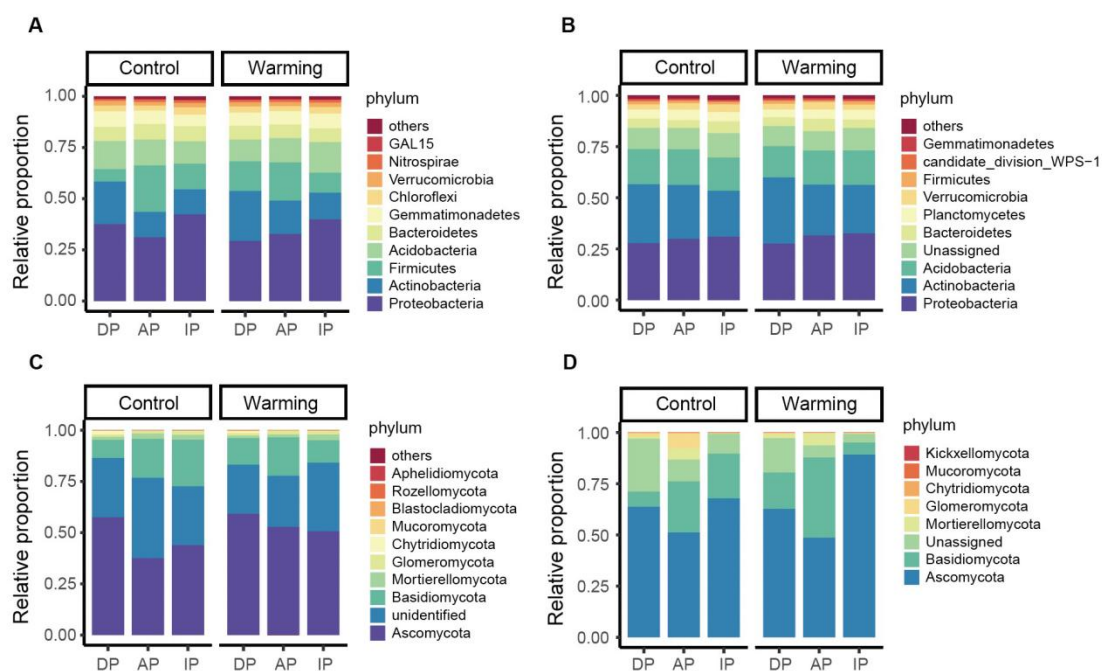


Figure S9 Relative abundance of bacterial (A; B) and fungal communities (C; D) under warming and precipitation changes. Only the 10 most abundant phylum-level taxa are shown.

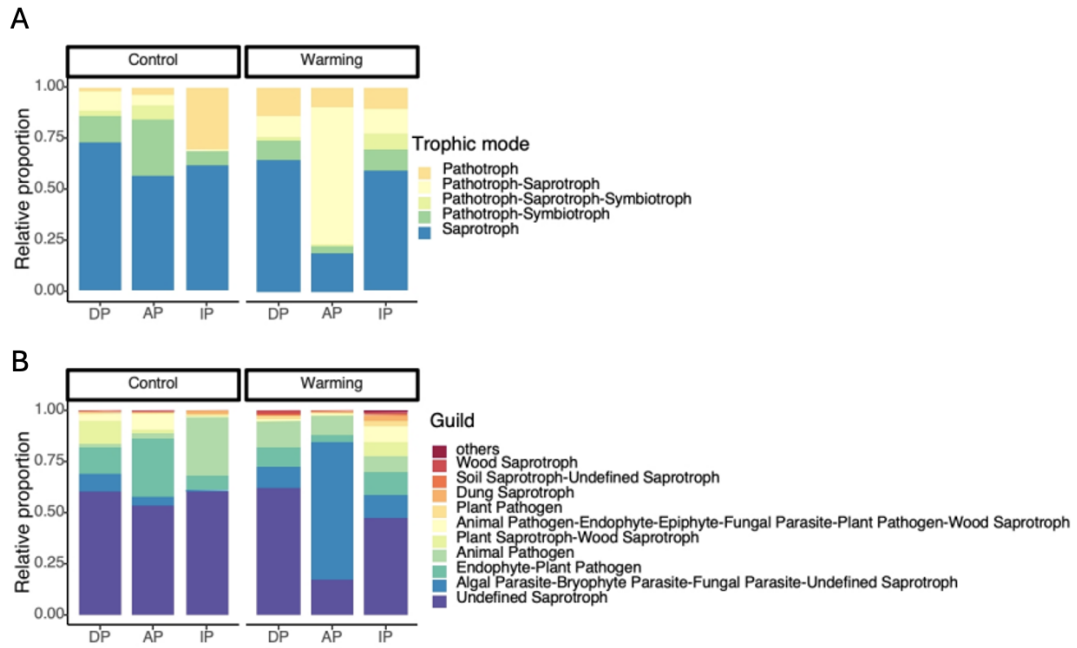


Figure S10 Variations in composition of trophic mode (B) and trophic mode (A) of Sordariomycetes inferred by FUNGuild. Treatments: DP: decreased precipitation, AP: ambient precipitation, IP: increased precipitation.

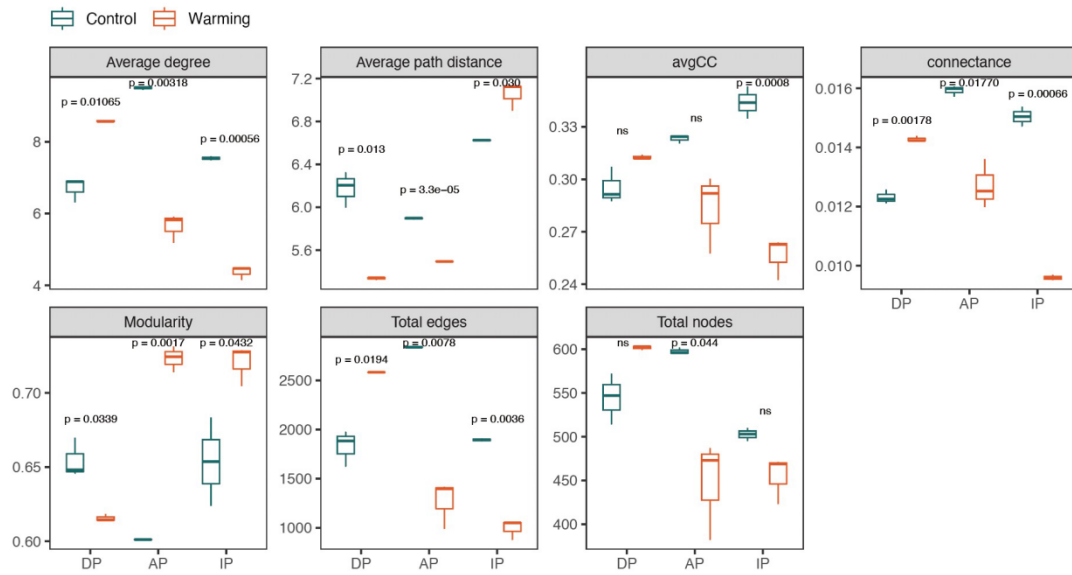


Figure S11 Microbial network topology parameters under warming and precipitation changes. Boxplots represent the minimum, maximum, median, first quartile and third quartile in the dataset. Asterisks indicate a significant difference (T-test) between ambient and warming treatments under different precipitation levels, ***: $P < 0.001$, **: $P < 0.010$, *: $P < 0.050$, and ns: $P > 0.050$. Treatments: DP: decreased precipitation, AP: ambient precipitation, IP: increased precipitation.

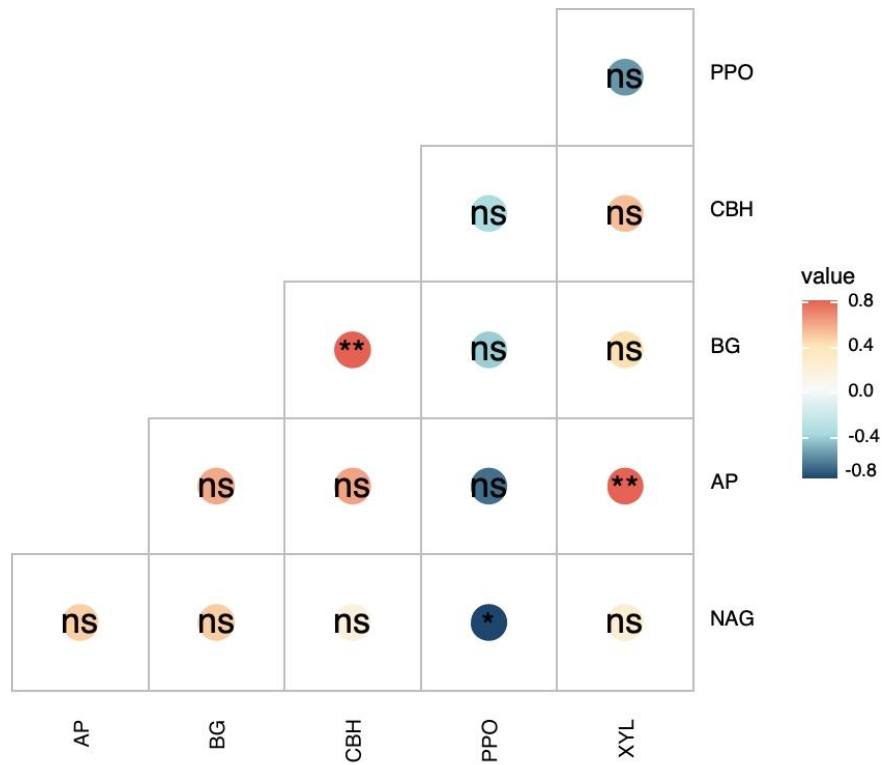


Figure S12 Pearson correlation between AP (Alkaline Phosphatase), BG (β -glucosidase), CBH (Circumcision- β -1,4-glucanase/cellobiose hydrolase), PPO (Polyphenol Oxidase), NAG (N-Acetylglucosaminidase) and XYL (β -xylosidase) enzyme activities under warming conditions. *** $P < 0.001$, ** $P < 0.010$, * $P < 0.050$, and ^{ns} $P > 0.050$.

Table S1 Results of the average pH, soil temperature, moisture, total phosphorus (TP), ammonia nitrogen (NH₄⁺-N), nitrate nitrogen (NO₃⁻-N), organic carbon (SOC), organic nitrogen (STN), inorganic carbon (DOC), inorganic nitrogen (DON), AP (Alkaline Phosphatase), BG (β -glucosidase), CBH (Circumcision- β -1,4-glucanase/cellobiose hydrolase), PPO (Polyphenol Oxidase), NAG (N-Acetylglucosaminidase) and XYL (β -xylosidase) enzyme activities under the six treatments.

	C	DP	IP	W	WDP	WIP
PH	8.58±0.09	8.45±0.03	8.49±0.08	8.50±0.04	8.38±0.02	8.48±0.04
Temperature	22.44±1.23	23.23±0.51	22.67±0.93	24.37±1.53	25.33±0.32	23.97±0.84
Moisture	24.51±1.14	20.72±0.78	27.83±1.56	22.88±1.30	19.38±0.40	27.61±0.41
NH ₄ ⁺ -N	5.14±0.24	4.68±0.09	5.09±0.10	4.49±0.31	5.55±0.91	4.57±0.39
NO ₃ ⁻ -N	0.80±0.05	0.62±0.04	1.34±0.28	0.71±0.06	0.70±0.02	0.81±0.10
SOC	5.65±0.64	6.19±0.60	6.30±1.08	5.90±0.77	5.87±0.97	5.97±0.64
STN	0.60±0.07	0.63±0.09	0.65±0.11	0.63±0.10	0.64±0.11	0.67±0.08
DOC	475.50±3.56	351.81±68.28	496.45±29.00	459.17±6.06	250.95±31.41	412.61±49.38
DON	35.04±1.03	31.11±5.77	35.46±8.67	29.64±1.95	29.24±1.92	28.98±2.79
NAG	1.74±0.99	3.38±0.84	2.62±1.33	1.61±0.47	1.00±0.61	1.64±0.56
AP	28.04±8.19	32.82±8.17	31.80±9.79	41.62±5.80	18.47±6.39	26.98±5.15
BG	24.75±11.27	36.44±2.87	29.82±7.63	36.30±8.94	12.79±5.35	27.45±10.56
CBH	14.27±2.29	14.94±2.20	17.90±6.84	15.21±6.09	6.77±3.87	14.04±2.21
PPO	1.92±0.80	4.65±2.56	5.35±2.63	2.85±1.06	4.38±0.62	3.89±2.21
XYL	9.51±0.95	9.72±2.41	9.15±0.62	9.60±0.34	9.78±0.80	9.73±0.79

Note: C: control, DP: decreased precipitation, IP: increased precipitation, W: warming, WDP: warming plus decreased precipitation, WIP: warming plus increased precipitation. Mean value and standard error of n = 3 biological replicates are shown.

Table S2 Effects (F-values) of warming (W) and precipitation changes (P, decreased

precipitation (DP) and increased precipitation (IP) were analyzed separately), and their interactions on microbial β -diversity in the 1st and 3rd years based on PERMANOVA.

	Bacteria						Fungi					
	1st year			3rd year			1st year			3rd year		
	R ²	F	P	R ²	F	P	R ²	F	P	R ²	F	P
W	0.026	0.596	0.946	0.108	1.933	0.031	0.071	1.677	0.011	0.136	2.516	0.009
P	0.206	2.725	0.001	0.311	3.389	0.001	0.132	1.596	0.008	0.335	3.781	0.001
IP	0.111	2.744	0.001	0.117	2.125	0.016	0.066	1.544	0.038	0.216	4.417	0.001
RP	0.086	2.062	0.011	0.193	3.819	0.001	0.084	2.010	0.004	0.147	2.758	0.006
W*P	0.065	0.835	0.741	0.130	1.731	0.022	0.092	1.177	0.157	0.293	7.443	0.001
W*IP	0.030	0.709	0.826	0.062	1.224	0.216	0.051	1.247	0.172	0.166	4.816	0.001
W*RP	0.041	0.969	0.493	0.060	1.315	0.156	0.035	0.860	0.679	0.126	2.986	0.002

Table S3 Topological properties of the microbial networks under warming and precipitation changes. Treatments: DP: decreased precipitation, WDP: warming plus

decreased precipitation, AP: ambient precipitation, W: warming, IP: increased precipitation, WIP: warming plus increased precipitation.

		DP	WDP	AP	W	IP	WIP
Year		2023	2023	2023	2023	2023	2023
Empirical networks	Total nodes	572	603	602	487	511	471
	Total edges	1978	2583	2844	1418	1916	1053
	Bacterial nodes (%)	62.6% (37.4%)	62.3% (37.7%)	59.4% (40.6%)	72.3% (27.3%)	70.4% (29.6%)	78.2% (21.8%)
	Positive correlation (%)	86.9% (13.1%)	90.6% (9.4%)	89.1% (10.9%)	78.7% (21.3%)	87.1% (12.9%)	72.5% (27.5%)
	Interactions between bacteria and fungi (%)	8.9%	8.0%	6.8%	9.0%	4.0%	9.8%
	R ² of power law connectance	0.962	0.986	0.977	0.955	0.974	0.977
	Average degree	6.916	8.567	9.449	5.823	7.499	4.471
	Average path distance	5.996	5.342	5.902	5.491	6.618	7.124
	Average clustering coefficient	0.307	0.312	0.321	0.300	0.352	0.263
	No. of large modules	11	15	10	13	12	14
	Modularity	0.670	0.614	0.601	0.731	0.635	0.728
	Vulnerability	0.047	0.035	0.033	0.034	0.064	0.068
	Robustness(random)	0.333 (±0.0132)	0.343 (±0.012)	0.340 (±0.013)	0.302 (±0.014)	0.318 (±0.0151)	0.289 (±0.017)
	Average path distance	3.400*** (±0.027)	3.219*** (±0.026)	3.149*** (±0.022)	3.531*** (±0.032)	3.236*** (±0.033)	3.934*** (±0.044)
	Random networks	Average clustering coefficient	0.006*** (±0.003)	0.009*** (±0.003)	0.010*** (±0.003)	0.007*** (±0.003)	0.008*** (±0.003)
Modularity		0.328*** (±0.004)	0.279*** (±0.004)	0.259*** (±0.003)	0.372*** (±0.004)	0.300*** (±0.004)	0.461*** (±0.005)

Table S4 Results of the T-test comparing topological properties of networks under warming and precipitation changes. Treatments: DP: decreased precipitation, AP:

ambient precipitation, IP: increased precipitation. *** $P < 0.001$, ** $P < 0.010$, * $P < 0.050$, and ^{ns} $P > 0.050$.

	Complexity	Vulnerability	Robustness
DP	*	*	*
AP	*	ns	*
IP	***	ns	*