Supporting Information

Biostimulant benefits under deficit irrigation do not ensure water saving compensation: A dual benchmark analysis of reproductive sink limitation in cotton

Table S1. Seed cotton yield, yield components, irrigation water productivity, and statistical comparisons among treatments.

Code	Yield (kg ha^{-1})	Bolls plant^{-1}	Boll mass (g)	IWP (kg m^{-3})	Adjusted P vs. W2 CK
T0	3734.3 ± 72.5	4.00	4.29	1.037	—
T1	4381.0 ± 53.1	4.00	5.04	1.217	0.004
T2	4134.5 ± 398.4	3.67	5.22	1.148	0.959
T3	4246.0 ± 701.5	3.67	5.33	1.179	0.970
T4	3041.3 ± 16.5	3.00	4.66	0.845	0.022
T5	3719.5 ± 489.8	3.67	4.69	1.033	0.970
T6	4234.2 ± 666.9	3.67	5.31	1.176	0.970
T7	4442.9 ± 564.7	4.33	4.72	1.234	0.959
T8	4511.9 ± 621.8	4.33	4.79	1.253	0.959
T9	4835.9 ± 654.3	4.67	4.76	1.343	0.689
T10	6391.3 ± 605.7	5.67	5.19	1.775	0.127
T11	6072.8 ± 566.2	5.67	4.93	1.350	—
T12	6190.6 ± 592.9	5.67	5.02	1.376	—
T13	7355.1 ± 357.9	6.33	5.35	1.634	—
T14	6559.0 ± 671.7	5.67	5.32	1.458	—
T15	6371.2 ± 587.7	5.67	5.17	1.416	—
T16	6073.9 ± 583.1	5.67	4.93	1.350	—
T17	6553.1 ± 614.6	5.67	5.32	1.456	—
T18	6381.0 ± 547.8	5.67	5.18	1.418	—

Table S2. Plant dry mass and reproductive allocation across growth stages.

Stage	Code	*n*	Total g plant^{-1}	Reproductive g plant^{-1}	Fraction %	*n* screened	Screened total g

Stage	Code	*n*	Total g plant^{-1}	Reproductive g plant^{-1}	Fraction %	*n* screened	Screened total g
S	T0	3	7.73 ± 1.05	0.21 ± 0.09	2.7 ± 0.8	2	7.13
S	T1	3	6.10 ± 1.29	0.32 ± 0.03	5.4 ± 1.3	3	6.10
S	T2	3	7.29 ± 1.96	0.31 ± 0.02	4.5 ± 1.0	3	7.29
S	T3	3	4.55 ± 2.24	0.22 ± 0.02	5.7 ± 2.7	3	4.55
S	T4	3	8.23 ± 3.59	0.46 ± 0.26	5.3 ± 1.5	3	8.23
S	T5	3	8.54 ± 1.49	0.29 ± 0.15	3.3 ± 1.4	3	8.54
S	T6	3	13.79 ± 1.20	0.84 ± 0.08	6.1 ± 0.3	3	13.79
S	T7	3	10.75 ± 0.89	0.81 ± 0.19	7.5 ± 1.6	3	10.75
S	T8	3	11.31 ± 0.35	0.71 ± 0.25	6.2 ± 2.0	3	11.31
S	T9	3	13.74 ± 0.57	0.98 ± 0.07	7.1 ± 0.2	3	13.74
S	T10	3	12.92 ± 2.00	1.24 ± 0.05	9.8 ± 1.5	3	12.92
S	T11	3	12.33 ± 0.23	0.70 ± 0.27	5.7 ± 2.3	3	12.33
S	T12	3	5.67 ± 1.50	0.71 ± 0.11	12.9 ± 2.1	3	5.67
S	T13	3	7.70 ± 0.79	0.39 ± 0.16	5.1 ± 1.8	3	7.70
S	T14	3	8.25 ± 2.58	0.51 ± 0.43	5.5 ± 4.8	3	8.25
S	T15	3	9.64 ± 1.88	0.69 ± 0.41	6.8 ± 3.3	3	9.64
S	T16	3	4.69 ± 0.66	0.50 ± 0.17	10.8 ± 3.9	3	4.69
S	T17	3	9.58 ± 1.18	0.42 ± 0.06	4.5 ± 1.1	3	9.58
S	T18	3	11.85 ± 1.56	0.09 ± 0.02	0.8 ± 0.1	3	11.85
F	T0	3	34.26 ± 20.46	21.84 ± 15.70	60.3 ± 9.2	3	34.26
F	T1	3	19.53 ± 2.57	10.01 ± 2.76	50.6 ± 7.3	3	19.53
F	T2	3	45.43 ± 2.46	23.87 ± 4.06	52.4 ± 7.1	3	45.43
F	T3	3	32.22 ± 3.46	15.80 ± 4.18	48.5 ± 7.7	3	32.22
F	T4	3	34.05 ± 2.98	18.24 ± 0.92	54.0 ± 7.1	3	34.05
F	T5	3	39.16 ± 0.80	20.25 ± 2.60	51.7 ± 7.0	3	39.16

Stage	Code	*n*	Total g plant^{-1}	Reproductive g plant^{-1}	Fraction %	*n* screened	Screened total g
F	T6	3	50.24 ± 0.66	29.32 ± 1.70	58.4 ± 2.9	3	50.24
F	T7	3	64.07 ± 2.53	43.82 ± 5.05	68.3 ± 6.2	3	64.07
F	T8	3	32.15 ± 3.97	15.67 ± 4.28	48.1 ± 7.9	3	32.15
F	T9	3	44.71 ± 13.29	27.54 ± 13.36	58.9 ± 13.6	3	44.71
F	T10	3	41.08 ± 0.95	23.77 ± 1.54	57.8 ± 2.4	3	41.08
F	T11	3	55.90 ± 3.11	26.35 ± 1.13	47.3 ± 4.2	3	55.90
F	T12	3	34.96 ± 2.22	15.42 ± 0.33	44.2 ± 2.0	3	34.96
F	T13	3	38.25 ± 4.09	17.83 ± 2.30	46.6 ± 2.9	3	38.25
F	T14	3	60.08 ± 8.02	28.68 ± 6.17	47.4 ± 3.9	3	60.08
F	T15	3	63.66 ± 8.80	39.13 ± 7.88	61.1 ± 4.0	3	63.66
F	T16	3	77.38 ± 25.10	47.59 ± 20.79	60.1 ± 8.9	3	77.38
F	T17	3	67.26 ± 13.19	31.88 ± 8.23	47.1 ± 3.4	3	67.26
F	T18	3	38.25 ± 1.75	15.98 ± 1.17	41.8 ± 3.3	3	38.25
B	T0	3	53.31 ± 1.21	31.77 ± 1.84	59.6 ± 2.2	2	53.92
B	T1	3	75.96 ± 10.83	46.01 ± 6.45	60.6 ± 0.3	3	75.96
B	T2	3	138.51 ± 2.44	86.06 ± 4.14	62.2 ± 3.6	3	138.51
B	T3	3	56.19 ± 17.30	28.83 ± 14.73	49.4 ± 9.7	3	56.19
B	T4	3	57.38 ± 4.57	30.92 ± 0.44	54.1 ± 3.6	3	57.38
B	T5	3	77.62 ± 30.48	46.74 ± 20.17	59.5 ± 3.8	3	77.62
B	T6	3	64.62 ± 6.11	29.89 ± 2.02	46.6 ± 7.0	3	64.62
B	T7	3	101.16 ± 12.90	45.55 ± 2.22	45.6 ± 7.6	2	94.35
B	T8	3	59.78 ± 3.41	33.11 ± 0.57	55.5 ± 2.2	3	59.78
B	T9	3	70.78 ± 17.64	45.31 ± 13.31	63.5 ± 3.3	3	70.78
B	T10	3	51.85 ± 7.26	35.57 ± 5.52	68.5 ± 1.9	3	51.85
B	T11	3	110.63 ± 9.77	52.02 ± 3.56	47.4 ± 7.4	3	110.63

Stage	Code	*n*	Total g plant^{-1}	Reproductive g plant^{-1}	Fraction %	*n* screened	Screened total g
B	T12	3	68.30 ± 11.17	40.06 ± 9.37	58.2 ± 4.0	3	68.30
B	T13	3	108.07 ± 13.62	61.06 ± 9.97	56.3 ± 2.2	3	108.07
B	T14	3	79.71 ± 5.49	46.89 ± 6.41	58.7 ± 4.2	3	79.71
B	T15	3	91.84 ± 9.32	51.81 ± 7.64	56.2 ± 2.5	3	91.84
B	T16	3	85.31 ± 9.74	51.18 ± 7.25	59.9 ± 1.6	2	79.86
B	T17	3	66.14 ± 9.11	39.65 ± 9.98	59.4 ± 7.2	3	66.14
B	T18	3	93.90 ± 5.32	45.68 ± 8.20	48.4 ± 6.0	3	93.90

Table S3. Leaf area and SPAD across growth stages.

Stage	Code	*n* leaf samples	Leaf area cm^2 sample^{-1}	n SPAD records	SPAD
S	T0	2	212.01 ± 47.77	3	56.67 ± 6.20
S	T1	2	277.75 ± 76.14	3	57.17 ± 3.61
S	T2	2	289.74 ± 34.54	3	60.47 ± 4.65
S	T3	2	182.07 ± 105.90	3	60.30 ± 7.90
S	T4	2	347.42 ± 142.98	3	62.47 ± 2.18
S	T5	2	298.71 ± 46.40	3	57.53 ± 3.33
S	T6	2	447.98 ± 123.87	3	58.93 ± 3.89
S	T7	2	369.70 ± 19.19	3	56.17 ± 2.11
S	T8	2	383.99 ± 45.49	3	59.63 ± 0.61
S	T9	2	504.05 ± 47.23	3	58.63 ± 3.96
S	T10	2	506.27 ± 17.59	3	60.17 ± 2.10
S	T11	2	683.61 ± 82.88	3	58.00 ± 3.82
S	T12	1	251.71 (*n*=1)	3	59.47 ± 0.76
S	T13	2	397.39 ± 29.93	3	58.73 ± 1.70
S	T14	1	447.16 (*n*=1)	3	60.43 ± 3.50

Stage	Code	*n* leaf samples	Leaf area cm^2 $sample^{-1}$	n SPAD records	SPAD
S	T15	2	526.43 ± 28.20	3	61.03 ± 0.86
S	T16	2	246.29 ± 2.13	3	60.63 ± 6.90
S	T17	2	320.76 ± 24.63	3	57.70 ± 4.07
S	T18	2	442.94 ± 68.54	3	61.90 ± 2.27
F	T0	2	564.40 ± 233.55	3	59.47 ± 2.60
F	T1	2	481.36 ± 191.54	3	59.70 ± 1.35
F	T2	2	1082.81 ± 182.96	3	60.73 ± 1.01
F	T3	2	701.28 ± 19.29	3	59.07 ± 2.35
F	T4	2	705.51 ± 133.52	3	61.30 ± 0.10
F	T5	2	867.06 ± 143.00	3	60.03 ± 0.32
F	T6	2	1120.91 ± 344.85	3	59.80 ± 2.75
F	T7	2	1101.27 ± 115.33	3	58.10 ± 2.59
F	T8	2	869.90 ± 20.52	3	58.97 ± 0.81
F	T9	2	784.12 ± 97.81	3	59.90 ± 2.16
F	T10	2	845.70 ± 73.48	3	61.13 ± 1.40
F	T11	2	1471.58 ± 230.91	3	59.53 ± 3.23
F	T12	2	931.29 ± 112.14	3	59.87 ± 1.72
F	T13	2	1035.14 ± 1.39	3	60.80 ± 0.46
F	T14	2	1788.41 ± 258.49	3	62.90 ± 3.10
F	T15	2	1378.52 ± 31.90	3	59.73 ± 1.69
F	T16	2	1603.06 ± 23.15	3	60.93 ± 3.76
F	T17	2	1890.45 ± 411.95	3	61.80 ± 4.45
F	T18	2	933.35 ± 203.26	3	62.27 ± 5.66
B	T0	2	861.54 ± 119.68	3	60.73 ± 1.03
B	T1	2	1177.22 ± 113.24	3	60.37 ± 1.60
B	T2	2	1947.14 ± 115.28	3	61.70 ± 2.71

Stage	Code	*n* leaf samples	Leaf area cm^2 $sample^{-1}$	n SPAD records	SPAD
B	T3	2	740.02 ± 338.46	3	58.67 ± 3.35
B	T4	2	855.25 ± 31.54	3	58.00 ± 2.26
B	T5	2	1213.81 ± 415.60	3	62.83 ± 2.97
B	T6	2	1336.69 ± 272.41	3	61.73 ± 4.07
B	T7	2	1260.10 ± 214.07	3	60.77 ± 3.93
B	T8	2	966.72 ± 191.83	3	61.03 ± 1.47
B	T9	2	1085.47 ± 133.71	3	62.57 ± 1.63
B	T10	2	670.66 ± 285.65	3	63.93 ± 2.68
B	T11	2	1895.91 ± 66.40	3	62.47 ± 2.84
B	T12	2	1138.96 ± 385.89	3	65.97 ± 1.23
B	T13	2	1718.47 ± 616.01	3	58.77 ± 0.86
B	T14	2	1243.41 ± 291.64	3	60.90 ± 3.91
B	T15	2	1489.20 ± 395.72	3	61.73 ± 3.87
B	T16	2	1090.37 ± 321.94	3	64.43 ± 3.00
B	T17	2	853.78 ± 78.73	3	60.73 ± 1.40
B	T18	2	1360.94 ± 73.20	3	66.20 ± 0.95

Table S4. Soil nutrient concentrations in the matched core treatment set.

Stage	Code	Depth cm	Nitrate N mg kg^{-1}	Available P mg kg^{-1}	Available K mg kg^{-1}
S	T0	0-20	2.27 ± 0.55	27.03 ± 8.11	216.07 ± 33.41
S	T0	20-40	15.50 ± 2.55	82.23 ± 6.23	454.87 ± 100.70
S	T1	0-20	4.17 ± 0.64	16.27 ± 11.04	371.23 ± 37.97
S	T1	20-40	38.47 ± 16.29	12.93 ± 5.97	292.73 ± 27.05
S	T2	0-20	15.20 ± 1.70	33.67 ± 13.50	344.03 ± 99.11
S	T2	20-40	33.40 ± 3.03	23.07 ± 2.86	299.30 ± 13.53

Stage	Code	Depth cm	Nitrate N mg kg^{-1}	Available P mg kg^{-1}	Available K mg kg^{-1}
S	T3	0-20	21.70 ± 12.92	21.07 ± 9.88	396.33 ± 57.33
S	T3	20-40	25.97 ± 0.61	21.03 ± 2.76	291.37 ± 27.88
S	T4	0-20	17.37 ± 1.66	16.63 ± 1.07	298.37 ± 2.80
S	T4	20-40	22.90 ± 6.10	25.30 ± 13.87	281.97 ± 56.92
S	T11	0-20	3.07 ± 0.21	91.77 ± 2.41	400.50 ± 20.72
S	T11	20-40	11.33 ± 3.55	41.13 ± 9.30	382.57 ± 24.10
S	T14	0-20	16.17 ± 12.36	40.47 ± 3.97	313.40 ± 28.62
S	T14	20-40	25.07 ± 2.45	21.87 ± 4.21	332.30 ± 25.55
S	T15	0-20	4.57 ± 1.14	28.17 ± 6.98	241.07 ± 9.35
S	T15	20-40	11.47 ± 4.23	39.67 ± 7.89	333.33 ± 11.56
S	T16	0-20	4.03 ± 0.40	10.60 ± 2.18	294.90 ± 15.65
S	T16	20-40	17.93 ± 2.27	30.80 ± 2.86	336.40 ± 16.85
S	T17	0-20	15.73 ± 20.59	18.20 ± 6.07	259.80 ± 16.03
S	T17	20-40	10.10 ± 1.25	10.03 ± 1.66	298.70 ± 19.28
F	T0	0-20	62.87 ± 26.66	20.94 ± 1.31	268.24 ± 10.93
F	T0	20-40	51.97 ± 14.16	20.70 ± 0.52	265.70 ± 15.62
F	T1	0-20	33.40 ± 6.34	19.07 ± 1.66	276.05 ± 8.50
F	T1	20-40	30.00 ± 15.77	22.47 ± 1.17	278.57 ± 6.07
F	T2	0-20	21.40 ± 2.77	23.17 ± 0.74	253.81 ± 8.83
F	T2	20-40	25.60 ± 14.64	22.27 ± 2.42	265.27 ± 13.68
F	T3	0-20	24.43 ± 4.31	22.00 ± 1.55	286.07 ± 12.95
F	T3	20-40	19.50 ± 5.69	24.67 ± 1.44	288.67 ± 0.74
F	T4	0-20	20.40 ± 3.47	19.97 ± 0.46	279.27 ± 21.59
F	T4	20-40	30.70 ± 6.71	14.77 ± 9.22	288.77 ± 4.04
F	T11	0-20	71.50 ± 43.65	28.27 ± 2.27	275.37 ± 17.47
F	T11	20-40	90.30 ± 80.21	21.93 ± 3.50	288.77 ± 31.30

Stage	Code	Depth cm	Nitrate N mg kg^{-1}	Available P mg kg^{-1}	Available K mg kg^{-1}
F	T14	0-20	23.97 ± 3.98	19.57 ± 2.34	249.63 ± 9.72
F	T14	20-40	25.57 ± 2.70	20.20 ± 3.15	236.07 ± 15.49
F	T15	0-20	43.83 ± 1.46	28.50 ± 2.89	311.70 ± 35.16
F	T15	20-40	46.23 ± 11.08	20.57 ± 4.84	298.37 ± 26.37
F	T16	0-20	38.47 ± 6.38	19.70 ± 1.56	231.10 ± 54.89
F	T16	20-40	21.17 ± 1.68	19.40 ± 2.74	258.43 ± 9.73
F	T17	0-20	33.77 ± 1.66	22.67 ± 3.50	264.33 ± 37.82
F	T17	20-40	34.83 ± 12.32	23.07 ± 3.61	269.33 ± 22.22
B	T0	0-20	16.98 ± 4.14	25.57 ± 0.83	260.97 ± 13.01
B	T0	20-40	18.70 ± 7.33	38.55 ± 4.72	321.98 ± 6.78
B	T1	0-20	15.61 ± 2.76	32.58 ± 4.43	274.22 ± 23.93
B	T1	20-40	31.12 ± 6.67	42.64 ± 1.12	289.84 ± 18.06
B	T2	0-20	18.72 ± 1.65	30.12 ± 1.54	294.66 ± 23.17
B	T2	20-40	27.61 ± 7.42	24.57 ± 7.36	301.84 ± 9.65
B	T3	0-20	9.79 ± 6.33	28.12 ± 6.94	268.74 ± 50.72
B	T3	20-40	7.79 ± 2.11	43.04 ± 10.51	295.40 ± 14.53
B	T4	0-20	13.60 ± 4.11	41.35 ± 8.56	274.91 ± 38.53
B	T4	20-40	16.38 ± 3.82	33.20 ± 5.50	340.48 ± 19.10
B	T11	0-20	2.41 ± 0.40	64.47 ± 7.51	296.24 ± 18.64
B	T11	20-40	1.75 ± 0.47	35.80 ± 3.45	313.39 ± 7.61
B	T14	0-20	6.14 ± 0.59	26.51 ± 1.91	255.58 ± 21.59
B	T14	20-40	6.57 ± 9.28	18.82 ± 2.62	243.63 ± 11.27
B	T15	0-20	1.84 ± 0.59	23.18 ± 3.59	253.03 ± 7.99
B	T15	20-40	12.19 ± 12.59	14.13 ± 4.15	243.06 ± 29.01
B	T16	0-20	22.20 ± 6.96	37.29 ± 8.40	249.32 ± 10.86
B	T16	20-40	22.06 ± 1.56	46.06 ± 33.62	219.64 ± 36.32

Stage	Code	Depth cm	Nitrate N mg kg^{-1}	Available P mg kg^{-1}	Available K mg kg^{-1}
B	T17	0-20	6.77 ± 0.97	30.05 ± 1.45	250.53 ± 5.00
B	T17	20-40	7.39 ± 0.65	25.62 ± 10.98	232.15 ± 22.96

Table S5. Descriptive associations between biomass and seed cotton yield.

Treatment mean set	Stage	Mass series	n means	Pearson *r*	Spearman rho
All 19 descriptive	F	Raw mass	19	0.417	0.379
All 19 descriptive	B	Raw mass	19	0.246	0.249
Core 10 CK1=T11	F	Raw mass	10	0.829	0.697
Core 10 CK1=T11	F	Mass screened	10	0.829	0.697
Core 10 CK1=T11	B	Raw mass	10	0.245	0.345
Core 10 CK1=T11	B	Mass screened	10	0.227	0.345
Core 10 CK1=T18	F	Raw mass	10	0.722	0.564
Core 10 CK1=T18	B	Raw mass	10	0.217	0.382
Within W2 five levels	F	Raw mass	5	-0.248	-0.600
Within W2 five levels	B	Raw mass	5	0.354	0.300
Within W1 CK1=T11	F	Raw mass	5	-0.191	0.100
Within W1 CK1=T11	B	Raw mass	5	-0.741	-0.800
Within W1 CK1=T18	F	Raw mass	5	-0.365	-0.500
Within W1 CK1=T18	B	Raw mass	5	-0.489	-0.500

Table S6. Sensitivity of treatment-level yield contrasts to alternative reference treatments.

Treatment code	Reference treatment code	Estimated yield of treatment (kg ha^{-1})	Estimated yield of reference treatment (kg ha^{-1})	Relative difference (%)
T1	T0	4381.0	3734.3	17.32
T2	T0	4134.5	3734.3	10.72

Treatment code	Reference treatment code	Estimated yield of treatment (kg ha^{-1})	Estimated yield of reference treatment (kg ha^{-1})	Relative difference (%)
T3	T0	4246.0	3734.3	13.70
T4	T0	3041.3	3734.3	-18.56
T5	T0	3719.5	3734.3	-0.40
T6	T0	4234.2	3734.3	13.39
T7	T0	4442.9	3734.3	18.97
T14	T11	6559.0	6072.8	8.01
T15	T11	6371.2	6072.8	4.91
T16	T11	6073.9	6072.8	0.02
T17	T11	6553.1	6072.8	7.91
T14	T18	6559.0	6381.0	2.79
T15	T18	6371.2	6381.0	-0.15
T16	T18	6073.9	6381.0	-4.81
T17	T18	6553.1	6381.0	2.70
T8	T0	4511.9	3734.3	20.82
T9	T0	4835.9	3734.3	29.50
T10	T0	6391.3	3734.3	71.15
T12	T11	6190.6	6072.8	1.94
T13	T11	7355.1	6072.8	21.12
T18	T11	6381.0	6072.8	5.08
T8	T5	4511.9	3719.5	21.30
T9	T6	4835.9	4234.2	14.21
T10	T7	6391.3	4442.9	43.85
T12	T5	6190.6	3719.5	66.44
T13	T6	7355.1	4234.2	73.71
T18	T7	6381.0	4442.9	43.62

Table S7. Matched cross-regime compensation metrics used in the main text analysis.

Treatment	W1/W2 codes	Within W2 response (%)	Yield retention (%)	IWP change (%)	Boll number retention (%)	Boll mass retention (%)	F biomass retention (%)	B biomass retention (%)	Required W2 yield (kg ha^{-1})	Compensation gap (kg ha^{-1})	Additional W2 yield required (%)
PGA	T14/T1	17.3	66.8	−16.5	70.5	94.7	32.5	95.3	5247.2	866.2	19.8
KH	T15/T2	10.7	64.9	−18.9	64.7	101.0	71.4	150.8	5097.0	962.5	23.3
BAO	T16/T3	13.7	69.9	−12.6	64.7	108.1	41.6	65.9	4859.1	613.1	14.4
PP	T17/T4	−18.6	46.4	−42.0	52.9	87.6	50.6	86.8	5242.5	2201.2	72.4

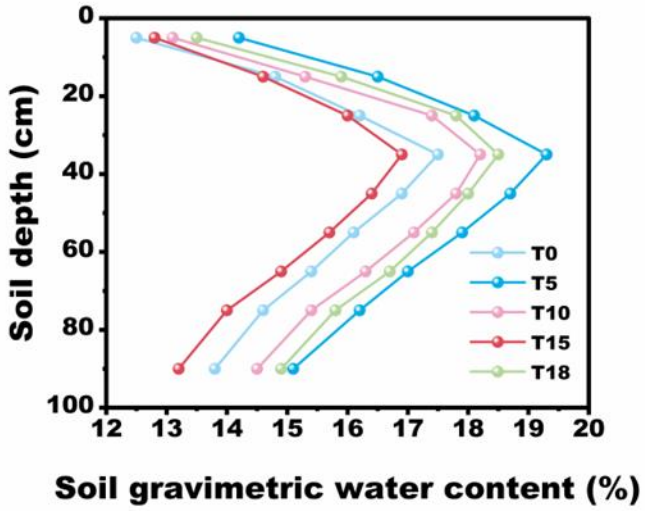


Figure S1 Soil water profiles by sampling round for the matched core set. Color shows mean recalculated gravimetric water content (%) after the review screen retaining values from 0% to 40%. All panels share a scale. Red asterisks indicate cells with fewer than three retained records; gray indicates no retained mean.

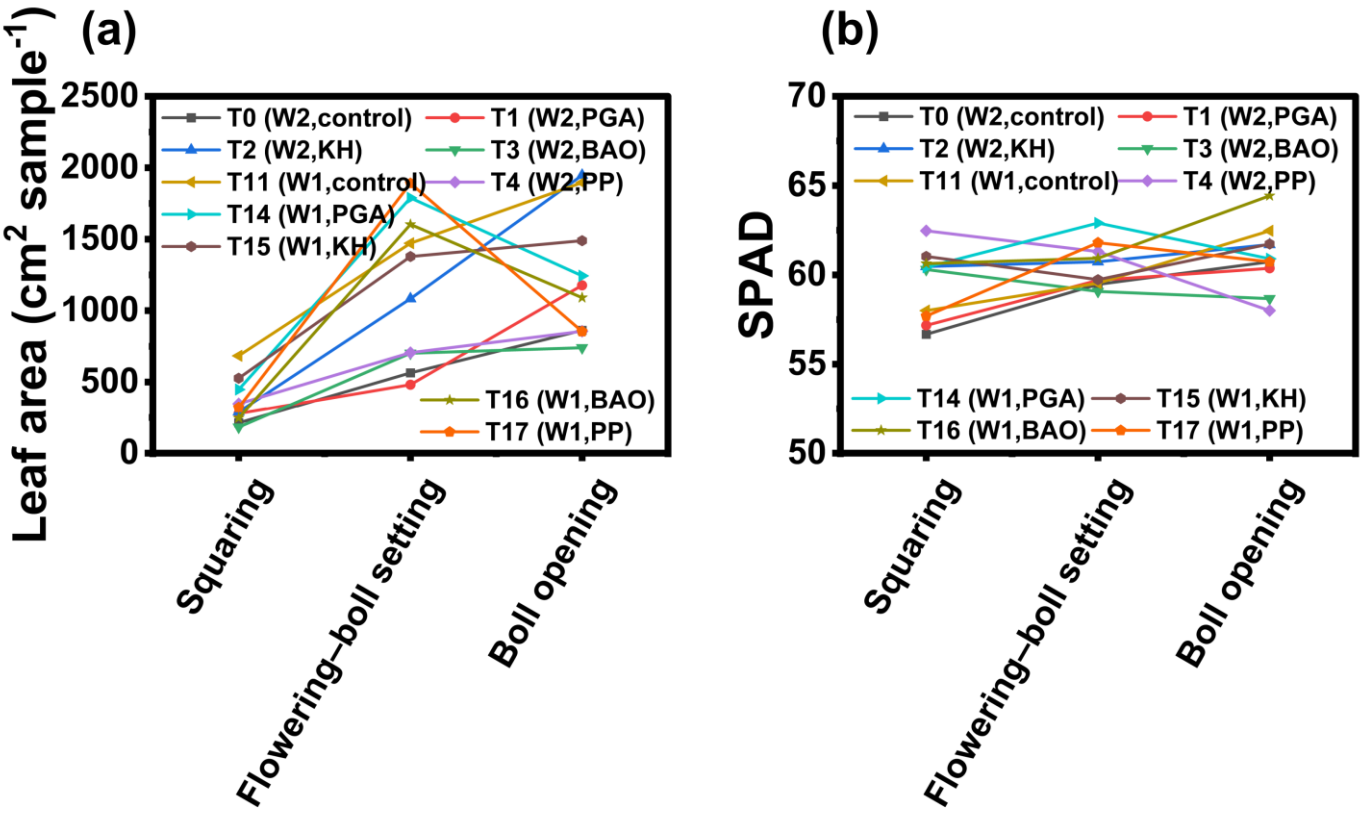


Figure S2 Leaf area and SPAD across the three labeled growth stages. Each line represents one matched core treatment mean; blue denotes W1 and orange W2. Leaf area is per complete labeled sample and is not leaf area index. SPAD is a meter reading and is not a direct photosynthetic rate. Numeric means, record level SD and sample counts are provided in Table S3.

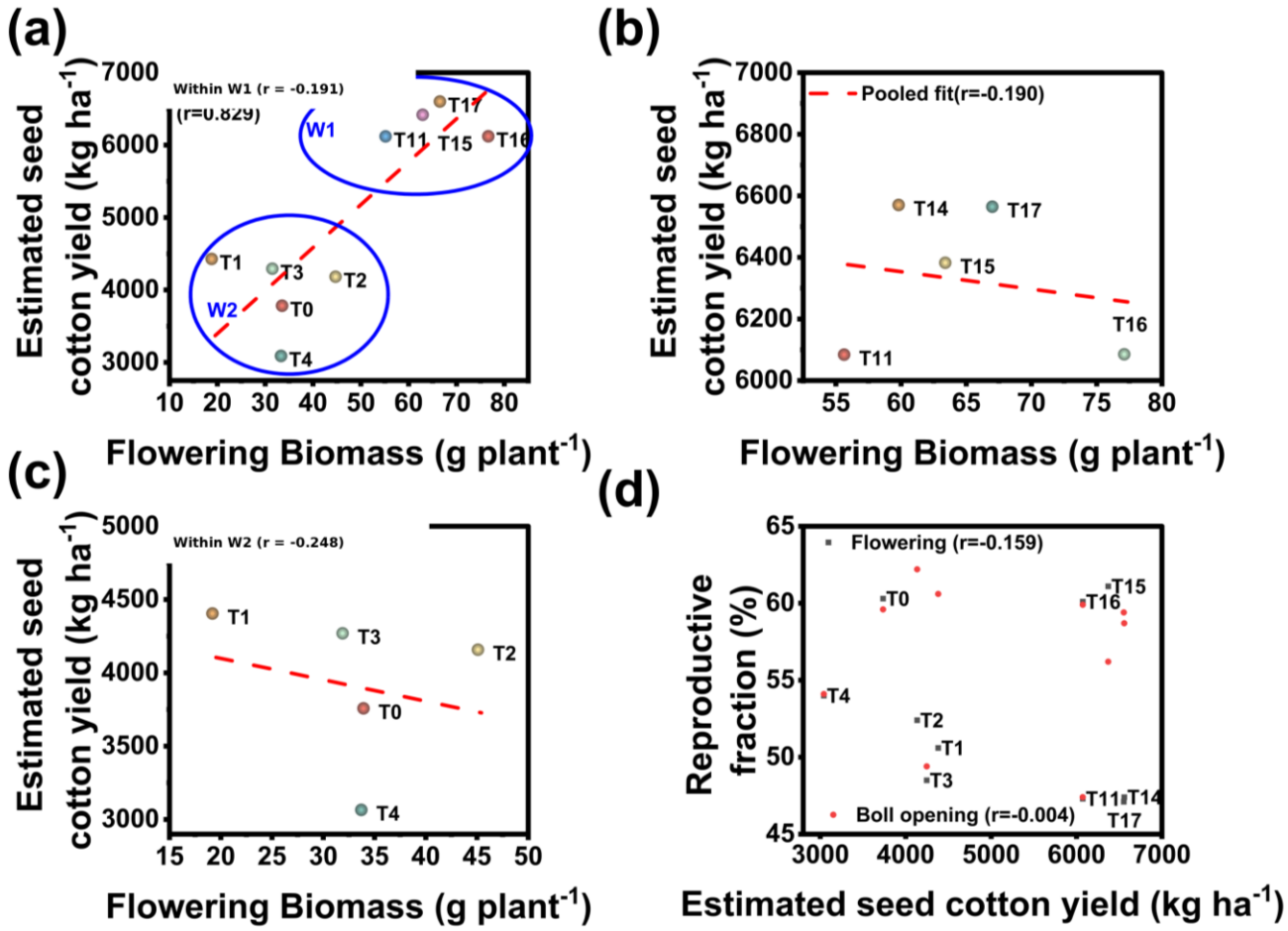


Figure S3. Biomass yield associations used as descriptive diagnostics. Panels show (a) pooled flowering–boll-setting biomass versus seed cotton yield, (b) the relationship within W1, (c) the relationship within W2, and (d) reproductive fraction versus seed cotton yield. The pooled flowering stage relationship was positive (Pearson r = 0.829), whereas within regime relationships were weakly negative (W1 r = −0.191; W2 r = −0.248). Correlations are based on treatment means and are interpreted descriptively.

Table S8. Treatment-code key for all T0–T18. W1 = 4500 m³ ha⁻¹; W2 = 3600 m³ ha⁻¹; PGA = poly-γ-glutamic acid; KH = potassium humate; BAO = brown algal oligosaccharides; PP = plant polyphenols. Rates are seasonal totals (kg ha⁻¹); combination rates are the sum of component rates, and 1.5× combinations scale both components.

Code	Treatment identity / irrigation (verified information only)	Use and verification status
T0	CK; W2; seasonal dose: 0 kg ha⁻¹	Untreated within-irrigation control

T1	PGA; W2; seasonal dose: 15 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T2	KH; W2; seasonal dose: 10 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T3	BAO; W2; seasonal dose: 0.5 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T4	PP; W2; seasonal dose: 0.3 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T5	PP + PGA; W2; seasonal dose: PP 0.3; PGA 15 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T6	PP + BAO; W2; seasonal dose: PP 0.3; BAO 0.5 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T7	PP + KH; W2; seasonal dose: PP 0.3; KH 10 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T8	PP + PGA (1.5×); W2; seasonal dose: PP 0.45; PGA 22.5 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T9	PP + BAO (1.5×); W2; seasonal dose: PP 0.45; BAO 0.75 kg ha^{-1}	Confirmed treatment allocation; compare within the same

		irrigation regime; matched W1/W2 comparisons only for identical formulations
T10	PP + KH (1.5×); W2; seasonal dose: PP 0.45; KH 15 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T11	CK; W1; seasonal dose: 0 kg ha^{-1}	Untreated within-irrigation control
T12	PP + PGA; W1; seasonal dose: PP 0.3; PGA 15 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T13	PP + BAO; W1; seasonal dose: PP 0.3; BAO 0.5 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T14	PGA; W1; seasonal dose: 15 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T15	KH; W1; seasonal dose: 10 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T16	BAO; W1; seasonal dose: 0.5 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T17	PP; W1; seasonal dose: 0.3 kg ha^{-1}	Confirmed treatment allocation; compare within the same irrigation regime; matched W1/W2 comparisons only for identical formulations
T18	PP + KH; W1; seasonal dose: PP	Confirmed treatment allocation; compare within the same

	0.3; KH 10 kg ha^{-1}	irrigation regime; matched W1/W2 comparisons only for identical formulations

Table S3 reports estimated leaf area per plant, not leaf area index. Representative leaves were used to obtain leaf length (L) and maximum width (W); the estimate was calculated as LA_est (cm² plant^{-1}) = 0.75 × mean(L × W) × N, where N is the total leaf count per plant. The number and canopy positions of representative leaves should be added when verified against the field sampling sheet.

Table S9. Dual-benchmark performance and yield-component retention.

Formulation	W1/W2	W1 yield ± SD	W2 yield ± SD	Retention (%)	Raw P	Holm P
PGA	T14/T1	6559.0 ± 671.7	4381.0 ± 53.1	66.8	0.0296	0.0539
KH	T15/T2	6371.2 ± 587.7	4134.5 ± 398.4	64.9	0.0079	0.0394
BAO	T16/T3	6073.9 ± 583.1	4246.0 ± 701.5	69.9	0.0270	0.0539
PP	T17/T4	6553.1 ± 614.6	3041.3 ± 16.5	46.4	0.0100	0.0401
PP+PGA	T12/T5	6190.6 ± 592.9	3719.5 ± 489.8	60.1	0.0057	0.0369
PP+BAO	T13/T6	7355.1 ± 357.9	4234.2 ± 666.9	57.6	0.0053	0.0369
PP+KH	T18/T7	6381.0 ± 547.8	4442.9 ± 564.7	69.6	0.0130	0.0401

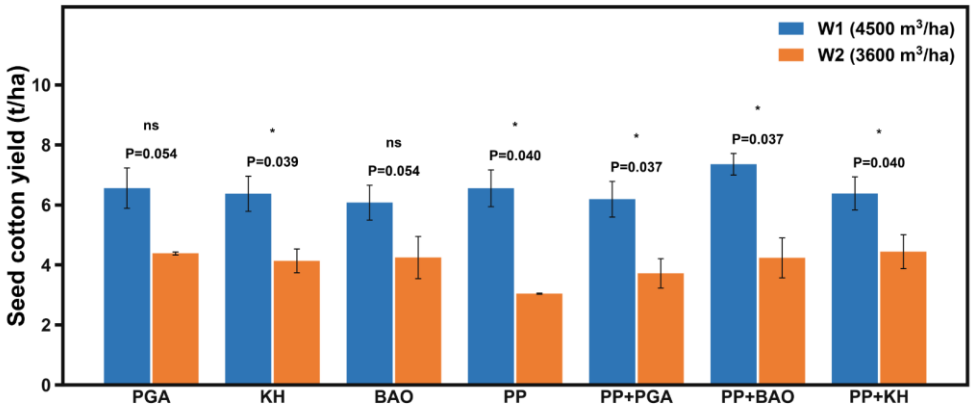


Figure S4. Seed cotton yield for seven dose-matched W1/W2 formulation pairs (PGA, KH, BAO, PP, PP+PGA, PP+BAO and PP+KH). Bars show treatment means ± SD (n = 3 independent plots per treatment). P values are two-sided Welch tests computed from reported means, SDs and sample sizes, with Holm adjustment across seven comparisons; ns, adjusted P ≥ 0.05; *, adjusted P < 0.05.



Figure S5. Photographic documentation of the field experiment

(a) Plastic-mulched rows during field establishment.



(b) Prepared experimental field and planting rows.



(c) Drip-irrigation distribution network and field layout.



(d) Drip-irrigation fittings and cotton plants during field growth.



(e) Overview of mulched cotton rows during establishment.

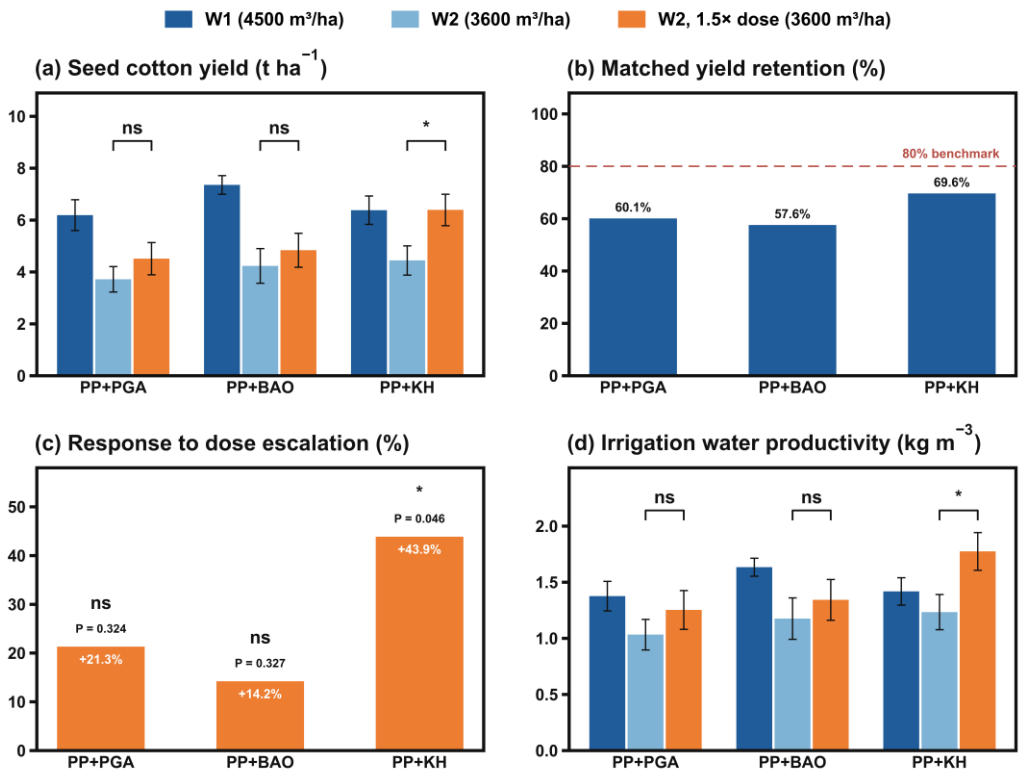


Figure S6. Seed cotton yield and irrigation water productivity responses to PP-based biostimulant combinations and dose escalation under contrasting irrigation regimes. (a) Measured seed cotton yield; (b) yield retention relative to the corresponding standard-dose W1 treatments; (c) relative yield increase following dose escalation under W2; and (d) irrigation water productivity (IWP). The dashed line in panel (b) represents the 80% yield-retention threshold required to maintain IWP following a 20% reduction in irrigation input. Error bars in panels (a) and (d) represent standard deviations (n = 3 independent plots per treatment). Relative responses in panels (b) and (c) were calculated from treatment means. Differences between standard and elevated doses under W2 were evaluated using two-sided Welch's t-tests based on group summary statistics, with Holm correction across the three formulations. * indicates an adjusted p-value below 0.05, and ns indicates a non-significant difference. Significance labels in panels (c) and (d) correspond to the yield comparisons in panel (a).

Table S10. Matched irrigation comparison and compensation gap.

Treatment	W1 4500 m^3 ha^{-1}	W2 3600 m^3 ha^{-1}
Untreated control	—	T0

Treatment	W1 4500 m^3 ha^{-1}	W2 3600 m^3 ha^{-1}
PGA	T14	T1
KH	T15	T2
BAO	T16	T3
PP	T17	T4

Table S11. Integrated response-state summary.

Treatment	Within W2 response (%)	Yield retention (%)	Distance from 80% boundary (percentage points)	IWP change (%)	Boll number retention (%)	Boll mass retention (%)
PGA	17.3	66.8	−13.2	−16.5	70.5	94.7
KH	10.7	64.9	−15.1	−18.9	64.7	101
BAO	13.7	69.9	−10.1	−12.6	64.7	108.1
PP	−18.6	46.4	−33.6	−42.0	52.9	87.6

Table S12. Treatment allocation and seasonal application rates.

Treatment	W1 yield (kg ha^{-1})	W2 yield (kg ha^{-1})	W1→W2 loss (kg ha^{-1})	Loss per irrigation saved (kg m^{-3})	Required W2 yield (kg ha^{-1})	Compensation gap (kg ha^{-1})	Additional W2 yield required (%)
PGA	6559	4381	2178	2.42	5247.2	866.2	19.8
KH	6371.2	4134.5	2236.7	2.49	5097	962.5	23.3
BAO	6073.9	4246	1827.9	2.03	4859.1	613.1	14.4
PP	6553.1	3041.3	3511.8	3.9	5242.5	2201.2	72.4

Product	Benchmark response	Yield component configuration	Biomass response	Integrated response state	Compensation outcome

Treatment		W1 4500 m^3 ha^{-1}		W2 3600 m^3 ha^{-1}	
PGA	+17.3% within W2; 66.8% retention	BN 70.5%; BM 94.7%	Terminal biomass 95.3%	Within regime benefit with incomplete sink preservation	13.2 percentage points below threshold
KH	+10.7%; 64.9% retention	BN 64.7%; BM 101.0%	Terminal biomass 150.8%	Late biomass recovery without reproductive recovery	Growth recovery did not close the sink number gap
BAO	+13.7%; 69.9% retention	BN 64.7%; BM 108.1%	Terminal biomass 65.9%	Sink size buffering under sink number limitation	Closest to compensation; 10.1 percentage points below threshold
PP	−18.6%; 46.4% retention	BN 52.9%; BM 87.6%	Terminal biomass 86.8%	Combined sink number and sink size loss	Largest compensation gap

$$DM_{total}=DM_{root}+DM_{stem}+DM_{leaf}+DM_{reproductive} \quad \textbf{(S1)}$$

$$RF(\%)=\frac{DM_{reproductive}}{DM_{total}}\times 100\% \quad (S2)$$

$$LA=L\times W\times N\times 0.75 \quad (S3)$$

$$Y=\frac{B\times M\times 217{,}500}{1000} \quad (S4)$$

$$IWP=\frac{Y}{IW} \quad (S5)$$

$$RB(\%)=\left(\frac{Y_{W2,treatment}}{Y_{W2,control}}-1\right)\times 100\% \quad (S6)$$

$$RR(\%)=\frac{Y_{W2,treatment}}{Y_{W1,treatment}}\times 100\% \quad (S7)$$

$$\frac{IW_{W2}}{IW_{W1}}=0.8 \quad (S8)$$

$$\frac{Y_{W2}}{Y_{W1}} \geq \frac{IW_{W2}}{IW_{W1}} = 0.8 \quad \text{(S9)}$$

$$R_{BN}(\%) = \frac{BN_{W2}}{BN_{W1}} \times 100\% \quad \text{(S10)}$$

$$R_{BM}(\%) = \frac{BM_{W2}}{BM_{W1}} \times 100\% \quad \text{(S11)}$$

$$R_{Bio}(\%) = \frac{Bio_{W2}}{Bio_{W1}} \times 100\% \quad \text{(S12)}$$

$$Y_{W2,required} = 0.8 \times Y_{W1} \quad \text{(S13)}$$

$$Gap = Y_{W2,required} - Y_{W2,observed} \quad \text{(S14)}$$

$$Gap_{relative}(\%) = \frac{Gap}{Y_{W2,observed}} \times 100\% \quad \text{(S15)}$$

$$P_{water} = \frac{Y_{W1} - Y_{W2}}{IW_{W1} - IW_{W2}} \quad \text{(S16)}$$

$$\ln\left(\frac{Y_{W2}}{Y_{W1}}\right) = \ln\left(\frac{BN_{W2}}{BN_{W1}}\right) + \ln\left(\frac{BM_{W2}}{BM_{W1}}\right) \quad \text{(S17)}$$