

Supplementary material:

Table S1. Detailed information of literature compiled in this meta-analysis. MAT, MAP, GT, LT, GI, GS, GD represent mean annual temperature, mean annual precipitation, grassland type, livestock type, grazing intensity, grazing season, and grazing duration, respectively; AM, AS, LG, MG, HG, AG, WSG, and CSG represent alpine meadow, alpine steppe, light grazing, moderate grazing, heavy grazing, annual grazing, warm-season grazing, and cold-season grazing, respectively.

Reference	Location	Elevation (m)	MAT (°C)	MAP (mm)	GT	LT	GI	GS	GD (year)
Ding et al., 2020	Haiyan, Qinghai	3100	1.4	350	AS	Sheep	MG	WSG	4
Ding et al., 2020	Haiyan, Qinghai	3100	1.4	350	AS	Yak	MG	WSG	4
Ding et al., 2020	Haiyan, Qinghai	3100	1.4	350	AS	Mixed	MG	WSG	4
Ding et al., 2020	Haiyan, Qinghai	3100	1.4	350	AS	Mixed	MG	WSG	4
Ding et al., 2020	Haiyan, Qinghai	3100	1.4	350	AS	Mixed	MG	WSG	4
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	LG	WSG	3
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	MG	WSG	3
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	HG	WSG	3
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	LG	CSG	3
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	MG	CSG	3
Dong et al., 2005	Dari, Qinghai	4000	-1.2	569	AM	Yak	HG	CSG	3
Du et al., 2020	Hongyuan, Sichuan	3500	1.1	752	AM	Yak	— ¹	—	8
Du, 2020	Tianzhu, Gansu	2960	0.1	415	AM	Mixed	LG	CSG	6
Du, 2020	Tianzhu, Gansu	2960	0.1	415	AM	Mixed	HG	CSG	6
Du, 2020	Tianzhu, Gansu	2960	0.1	415	AM	Mixed	—	AG	6
Du, 2020	Tianzhu, Gansu	2960	0.1	415	AM	Mixed	—	WSG	6
Gao et al., 2011	Hongyuan, Sichuan	3500	1.1	752	AM	Yak	HG	AG	11
Jiang et al., 2015	Naqu, Tibet	4450	-2.1	406	AM	Sheep	MG	AG	9
Lang et al., 2021	Shangri-La, Yunnan	3300	5.8	647	AM	Mixed	HG	AG	5
Lang et al., 2021	Shangri-La, Yunnan	3300	5.8	647	AM	Mixed	HG	CSG	5
Li et al., 2013	Tianzhu, Gansu	3000	0.6	—	AM	—	LG	—	3
Li et al., 2013	Tianzhu, Gansu	3000	0.6	—	AM	—	MG	—	3
Li et al., 2013	Tianzhu, Gansu	3000	0.6	—	AM	—	HG	—	3
Li et al., 2014a	Gangcha, Qinghai	—	-2.7	275	AS	—	HG	—	—
Li et al., 2014a	Menyuan, Qinghai	3250	-2	600	AM	—	HG	—	—
Li et al., 2016	Menyuan, Qinghai	3200	-2	500	AM	Sheep	MG	WSG	4
Li et al., 2018	Menyuan, Qinghai	3200	-1.7	580	AM	Sheep	LG	CSG	6
Li et al., 2018	Menyuan, Qinghai	3200	-1.7	580	AM	Sheep	MG	CSG	6
Li et al., 2018	Menyuan, Qinghai	3200	-1.7	580	AM	Sheep	HG	CSG	6
Li et al., 2020	Sunan, Gansu	2873	6	244	AM	Mixed	—	—	3
Li, 2016	Tianzhu, Gansu	2960	0.8	425	AM	Mixed	HG	CSG	4
Li, 2016	Tianzhu, Gansu	2960	0.8	425	AM	Mixed	HG	AG	4
Li, 2016	Tianzhu, Gansu	2960	0.8	425	AM	Mixed	—	CSG	4
Li, 2020	Tianzhu, Gansu	3022	0.2	417	AM	Mixed	—	—	6
Li, 2020	Tianzhu, Gansu	3022	0.2	417	AM	Mixed	—	—	6

Liu et al., 2020	Zoige, Sichuan	3740	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3721	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3725	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3736	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3702	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3695	—	—	AM	Mixed	—	—	1
Liu et al., 2020	Zoige, Sichuan	3678	—	—	AM	Mixed	—	—	1
Liu, 2005	Songpan, Sichuan	3400	2.8	718	AM		—	CSG	—
Lu et al., 2015	Tibet	—	—	—	AS	Mixed	—	AG	—
Lu et al., 2015	Tibet	—	—	—	AM	Mixed	—	AG	—
Ma et al., 2016	Hongyuan, Sichuan	3485	1.4	749	AM	Yak	—	WSG	6
Ma, 2021	Tianzhu, Gansu	—	-0.1	411	AM	Sheep	—		10
Nian, 2019	Qilian, Qinghai	3700	1.4	415	AM	Yak	—	WSG	2
Nian, 2019	Qilian, Qinghai	3700	1.4	415	AM	Yak	—	WSG	2
Nian, 2019	Qilian, Qinghai	3700	1.4	415	AM	Yak	—	WSG	2
Nian, 2019	Qilian, Qinghai	3700	1.4	415	AM	Yak	—	WSG	2
Qi, 2005	Gangcha, Qinghai	3250	-0.6	371	AS	—	—	CSG	3
Qi, 2005	Gangcha, Qinghai	3250	-0.6	371	AS	—	—	CSG	3
Qi, 2005	Gangcha, Qinghai	3250	-0.6	371	AS	—	—	CSG	3
Qi, 2005	Gangcha, Qinghai	3250	-0.6	371	AS	—	—	CSG	3
Qi, 2019	Maqu, Gansu	—	1.1	596	AM	Yak	MG	CSG	7
Qi, 2019	Maqu, Gansu	—	1.1	596	AM	Yak	MG	AG	7
Ren et al., 2021	Hongyuan, Sichuan	3504	1.5	749	AM	Yak	LG	WSG	4
Ren et al., 2021	Hongyuan, Sichuan	3504	1.5	749	AM	Yak	MG	WSG	4
Ren et al., 2021	Hongyuan, Sichuan	3504	1.5	749	AM	Yak	HG	WSG	4
Shi et al., 2010	Songpan, Sichuan	3400	2.8	718	AM	Yak	HG	CSG	8
Shi et al., 2010	Songpan, Sichuan	3400	2.8	718	AM	Yak	HG	CSG	8
Shi et al., 2013	Tianzhu, Gansu	3600	-0.1	416	AM	Mixed	HG	AG	9
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	LG	WSG	3
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	MG	WSG	3
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	HG	WSG	3
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	LG	CSG	3
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	MG	CSG	3
Song, 2016	Gangcha, Qinghai	3400	-0.6	435	AS	Sheep	HG	CSG	3
Su, 2015	Gongbujiangda, Tibet	4450	3.8	550	AM	Yak	MG	WSG	5
Su, 2015	Gongbujiangda, Tibet	4450	3.8	550	AM	Yak	MG	WSG	5
Su, 2015	Gongbujiangda, Tibet	4450	3.8	550	AM	Yak	HG	WSG	5
Su, 2015	Gongbujiangda, Tibet	4450	3.8	550	AM	Yak	HG	WSG	5
Sun et al., 2014	Shenzha, Tibet	4675	0	300	AS	—	—	AG	3
Sun et al., 2014	Shenzha, Tibet	4675	0	300	AS	—	—	CSG	3
Sun, 2012	Maqu, Gansu	3579	—	—	AM	Yak	LG	—	9
Sun, 2012	Maqu, Gansu	3579	—	—	AM	Yak	MG	—	9
Sun, 2012	Maqu, Gansu	3579	—	—	AM	Yak	HG	—	9
Tenzin et al., 2018	Nierong, Tibet	4600	-0.6	380.5	AM	—	—	AG	11

Wang et al., 2005	Dari, Qinghai	4090	-1.2	537	AM	—	—	CSG	6
Wang et al., 2010	Maqu, Gansu	3500	1.2	620	AM	—	LG	—	10
Wang et al., 2010	Maqu, Gansu	3500	1.2	620	AM	—	MG	—	10
Wang et al., 2010	Maqu, Gansu	3500	1.2	620	AM	—	HG	—	10
Wang et al., 2016	Menyuan, Qinghai	3400	-2.0	500	AM	—	—	CSG	4
Wang et al., 2016	Menyuan, Qinghai	3200	-2.0	500	AM	—	—	CSG	4
Wang, 2009	Gangcha, Qinghai	3280	-0.6	423	AS	—	—	CSG	8
Wang, 2019	Tianzhu, Gansu	3000	-0.1	416	AM	Yak	MG	—	15
Wang, 2019	Tianzhu, Gansu	3000	-0.1	416	AM	Yak	HG	—	15
Wei et al., 2012	NMD Co, Tibet	4730	-0.6	290	AS	Mixed	—	WSG	6
Wu et al., 2010	Maqu, Gansu	3500	1.2	620	AM	Mixed	MG	—	10
Wu et al., 2014	Menyuan, Qinghai	3545	1.3	560	AM	Sheep	LG	WSG	3
Wu et al., 2014	Menyuan, Qinghai	3545	1.3	560	AM	Sheep	MG	WSG	3
Wu et al., 2014	Menyuan, Qinghai	3545	1.3	560	AM	Sheep	HG	WSG	3
Wu et al., 2019	Hongyuan, Sichuan	—	1.7	756	AM	Yak	—	AG	14
Xiang et al., 2021	Linzhou, Tibet	3900	—	405	AS	Sheep	MG	WSG	4
Xiang et al., 2021	Linzhou, Tibet	3900	—	405	AS	Sheep	HG	WSG	4
Xue et al., 2018	Dangxiong, Tibet	—	1.3	477	AM	—	HG	CSG	8
Yang et al., 2009	Subei, Gansu	2055	6.3	183	AS	Sheep	LG	WSG	—
Yang et al., 2009	Subei, Gansu	2055	6.3	183	AS	Sheep	MG	WSG	—
Yang et al., 2009	Subei, Gansu	2055	6.3	183	AS	Sheep	HG	WSG	—
Yang et al., 2016b	Hongyuan, Sichuan	—	1.4	749	AM	—	—	WSG	3
Yang et al., 2016b	Hongyuan, Sichuan	—	1.4	749	AM	—	—	CSG	3
Yang et al., 2016b	Hongyuan, Sichuan	—	1.4	749	AM	—	—	AG	3
Yu et al., 2015	Tianzhu, Gansu	2960	-0.1	416	AM	—	LG	CSG	8
Yu et al., 2015	Tianzhu, Gansu	2960	-0.1	416	AM	—	LG	WSG	8
Yu et al., 2015	Tianzhu, Gansu	2960	-0.1	416	AM	—	MG	WSG	8
Yu et al., 2015	Tianzhu, Gansu	2960	-0.1	416	AM	—	HG	WSG	8
Yuan et al., 2020	Xidatan, Qinghai	4538	0	370	AM	Mixed	MG	AG	14
Yuan et al., 2020	Fenghuoshan, Qinghai	4768	-3	420	AM	Mixed	MG	AG	12
Yuan et al., 2020	Kaixinling, Qinghai	4627	-1.5	350	AM	Mixed	MG	AG	10
Yuan et al., 2020	Kaixinling, Qinghai	4627	-1.5	350	AM	Mixed	MG	AG	10
Yuan et al., 2020	Kaixinling, Qinghai	4627	-1.5	350	AM	Mixed	MG	AG	10
Zhai et al., 2017	Gangcha, Qinghai	3343	-0.5	607	AS	Sheep	LG	AG	5
Zhai et al., 2017	Gangcha, Qinghai	3343	-0.5	607	AS	Sheep	MG	AG	5
Zhai et al., 2017	Gangcha, Qinghai	3343	-0.5	607	AS	Sheep	MG	AG	5
Zhai et al., 2017	Gangcha, Qinghai	3343	-0.5	607	AS	Sheep	HG	AG	5
Zhai et al., 2017	Gangcha, Qinghai	3343	-0.5	607	AS	Sheep	HG	AG	5
Zhang et al., 2009	Menyuan, Qinghai	3200	-1.7	580	AM	—	—	CSG	10
Zhang et al., 2020	Luqu, Gansu	3550	2.3	707	AM	—	—	CSG	4
Zhang et al., 2021	Tianzhu, Gansu	2900	-1	416	AM	—	LG	—	4
Zhang, 2017	Hezuo, Gansu	2950	2.4	550	AM	—	MG	—	—
Zhang, 2020	Menyuan, Qinghai	3220	-1.1	417	AM	—	—	CSG	10
Zhang, 2021	Tianzhu, Gansu	2900	-0.1	416	AM	—	—	AG	5

Zhang, 2021	Tianzhu, Gansu	2900	-0.1	416	AM	—	—	CSG	5
Zhang, 2021	Tianzhu, Gansu	2900	-0.1	416	AM	—	—	CSG	5
Zhao et al., 2019	Dangxiong, Tibet	4400	—	—	AM	Mixed	—	—	11
Zhao et al., 2019	Dangxiong, Tibet	4500	—	—	AM	Mixed	—	—	11
Zhao et al., 2019	Dangxiong, Tibet	4650	—	—	AM	Mixed	—	—	11
Zhao et al., 2019	Dangxiong, Tibet	4800	—	—	AM	Mixed	—	—	11
Zhao et al., 2019	Dangxiong, Tibet	5100	—	—	AM	Mixed	—	—	11
Zhao et al., 2019	Dangxiong, Tibet	4950	—	—	AM	Mixed	—	—	11
Zhou et al., 2019	Maqin, Qinghai	—	1.4	603	AM	Yak	LG	—	—
Zhou et al., 2019	Maqin, Qinghai	—	1.4	603	AM	Yak	MG	—	—
Zhou et al., 2019	Maqin, Qinghai	—	1.4	603	AM	Yak	HG	—	—
Zhu et al., 2021	Shangri-La, Yunnan	3601	5.4	620	AM	Mixed	—	—	2
Zhu et al., 2021	Shangri-La, Yunnan	3601	5.4	620	AM	Mixed	—	—	2

¹ Data was not reported.

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Table S2. Statistical summary of soil organic carbon (SOC) stock and its changes after grazing in alpine meadow (AM) and alpine steppe (AS).

Variables	SOC stock of ungrazed treatment (Mg ha ⁻¹)		SOC stock of grazed treatment (Mg ha ⁻¹)		Change of SOC stock (Mg ha ⁻¹)		Annual change of SOC stock (Mg year ⁻¹)	
	AM	AS	AM	AS	AM	AS	AM	AS
Minimum	10.9	15.1	9.8	6.9	-119.4	-53.6	-14.4	-17.9
Maximum	222.1	159.8	196.6	121.7	28.1	10.2	7.7	3.4
Mean	95.8	74.1	85.5	64.2	-10.3	-9.8	-2.1	-4.3
Median	91.2	67.1	85.6	62.6	-5.1	-3.2	-0.7	-0.9
Variance	2664.9	1916.0	1980.3	886.7	456.2	321.1	20.0	48.8
Standard deviation	51.6	43.8	44.5	29.8	21.4	17.9	4.5	6.9
Standard error	5.0	7.9	4.3	5.3	2.1	3.2	0.5	1.3
Skewness	0.31	1.08	0.24	0.43	-1.77	-1.21	-0.58	-0.91
Kurtosis	-0.91	0.06	-0.65	-0.37	6.33	0.41	0.43	-0.81

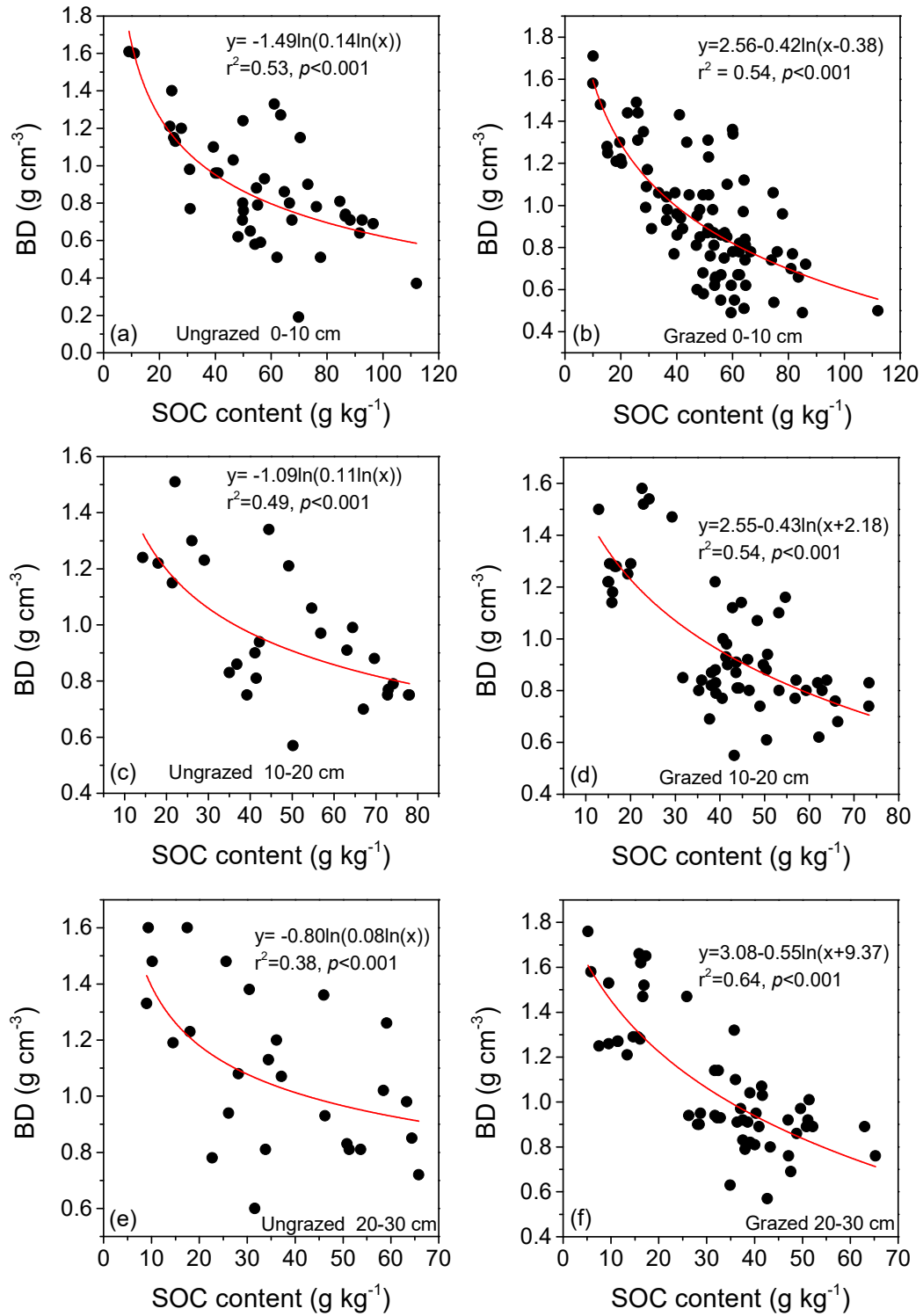


Figure S1. Relationships between bulk density (BD) and soil organic carbon (SOC) content in ungrazed (a: 0-10 cm; c: 10-20 cm; e: 20-30 cm) and grazed treatments (b: 0-10 cm; d: 10-20 cm; f: 20-30 cm).

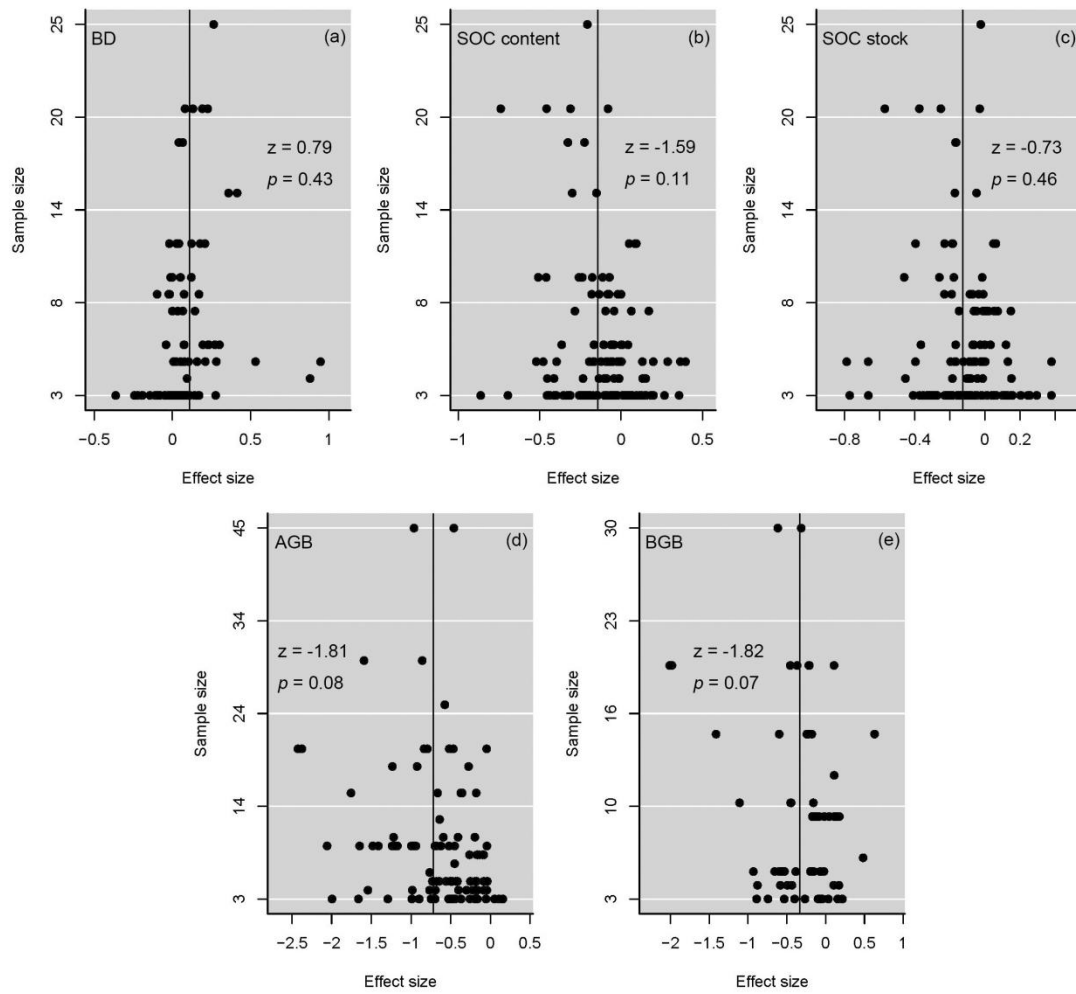


Figure S2. Funnel plots of changes in bulk density (BD) (a), soil organic carbon (SOC) content (b), SOC stock (c), plant above-ground biomass (AGB) (d), and below-ground biomass (BGB) (e). Results of publication bias tests using Egger's regression are given (z and p values). p value > 0.05 indicates the absence of publication bias.

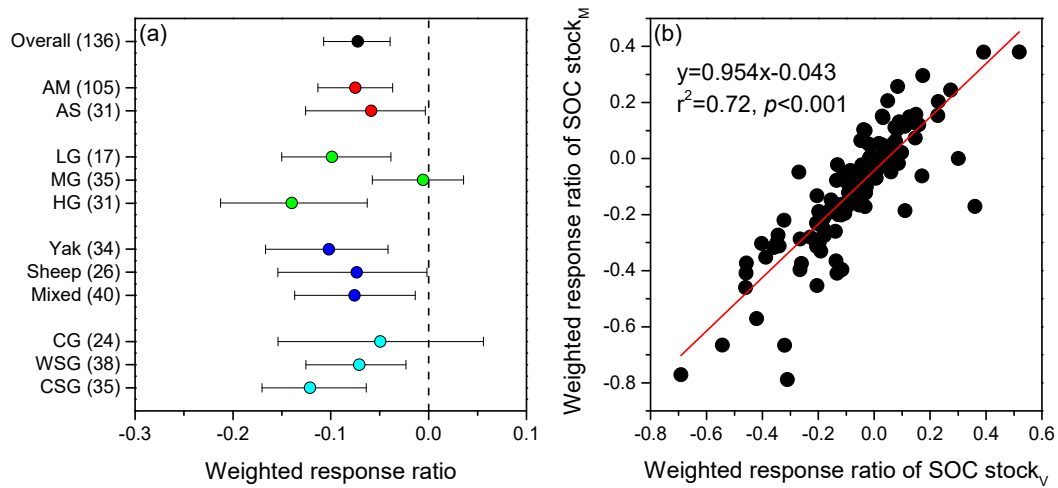


Figure S3. Weighted response ratios of soil organic carbon (SOC) stock calculated based on soil volume (a); relationship between weighted response ratios of SOC stock calculated based on volume (SOC stock_v) and those of SOC stock calculated based on mass (SOC stock_M) (b).

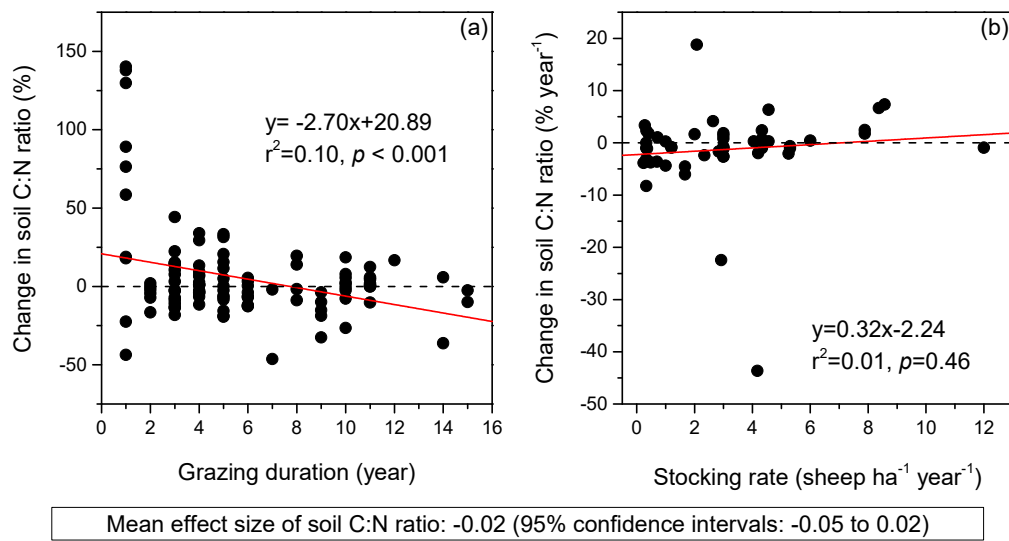


Figure S4. Relationships between the changes in soil carbon to nitrogen (C: N) ratio and grazing duration (a) as well as stocking rate (b).