Managing Soil Nitrogen Surplus: The Role of Winter Cover Crops in N_2O Emissions and Carbon Sequestration

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Supplementary material

Table S1. Mean water-filled pore space (WFPS %) values across different cropping phases. Means (n=4) ± (SD).

		Cover crop phase	Sugar beet phase	Winter wheat phase
G18	Fallow	60.1 (23.9)	53.2 (20.1)	80.4 (17.1)
	Winter rye	55.2 (24.1)	54.3 (21.8)	79.1 (15)
	Saia oat	54.4 (24.2)	53.5 (20.5)	78.9 (15.2)
	Spring vetch	56.8 (23.1)	53.2 (20)	78.9 (15.6)
H18	Fallow	66.4 (21)	48.1 (12.3)	69.5 (9.8)
	Winter rye	65.3 (24.5)	47.6 (14.6)	72.2 (8.3)
	Saia oat	64.1 (24.5)	45.9 (13.9)	71.7 (9.1)
	Spring vetch	68.2 (23.4)	48 (13.6)	72.5 (8.3)
G19	Fallow	68.6 (27)	47.1 (13.9)	69.8 (9.8)
	Winter rye	65.6 (17.9)	46.9 (15.2)	70.1 (11)
	Saia oat	63.2 (18)	46.9 (14.6)	70.7 (10.7)
	Spring vetch	63.4 (15.9)	45.9 (14.4)	70 (12.6)
H19	Fallow	73.1 (10.5)	53.8 (11.3)	69.1 (11.7)
	Winter rye	75.3 (12.5)	54.2 (13.6)	70.2 (11.3)
	Saia oat	74.1 (13.5)	53.4 (14.7)	67.4 (10.8)
	Spring vetch	76 (11.1)	52.8 (14.1)	68.7 (12.7)

Table S2. Topsoil mineral nitrogen (SMN) levels [kg N ha^{-1}] at key stages within the crop rotation. Means (n=4 for individual trials, n=16 for averages across all site-years; except for rye in the sugar beet and winter wheat phases n=12) ± (SD). Significant differences among treatments within each phase are indicated by lowercase letters ($p<0.05$).

		SMN [kg N ha^{-1}]									
		Cover crop phase						Sugar beet phase		Winter wheat phase	
Trial	Treatment	Sep	Oct	Nov	Jan	Feb	Apr	May	Sep	Nov	Mar
G18	Fallow	80 (8)	130 (16)	141 (51) a	17 (4)	33 (5) a	29 (2) a	178 (47)	26 (23)	66 (8)	13 (2)
	Winter rye	81 (30)	121 (7)	14 (3) b	16 (3)	35 (12) ac	30 (8) a	156 (11)	14 (7)	60 (11)	12 (2)
	Saia oat	94 (6)	139 (46)	31 (2) b	34 (11)	95 (16) b	57 (14) b	159 (10)	13 (4)	72 (18)	13 (2)
	Spring vetch	85 (5)	130 (29)	66 (10) b	28 (5)	55 (3) c	48 (10) ab	247 (74)	15 (3)	69 (15)	12 (2)
H18	Fallow	27 (8)	50 (7)	54 (7) a	5 (1) ab	8 (2) a	13 (4) a	155 (167)	5 (2)	37 (29)	7 (1)
	Winter rye	27 (7)	67 (26)	5 (0.4) b	2 (1) a	7 (1) a	4 (2) b	176 (58)	3 (0)	20 (4)	5 (1)
	Saia oat	33 (7)	57 (6)	5 (1) b	4 (2) ab	15 (1) b	13 (4) a	144 (60)	4 (1)	23 (12)	7 (2)
	Spring vetch	29 (1)	62 (17)	25 (14) c	6 (2) b	15 (4) b	19 (2) a	188 (75)	9 (7)	16 (7)	4 (1)
G19	Fallow	58 (14)	98 (10)	107 (38) a	38 (22)	39 (25)	20 (2)	120 (84)	20 (4)	42 (10)	29 (8)
	Winter rye	52 (20)	40 (13)	31 (16) b	19 (4)	24 (2)	18 (5)	168 (72)	28 (4)	59 (9)	30 (4)
	Saia oat	42 (10)	129 (119)	38 (11) b	34 (14)	49 (14)	20 (2)	119 (80)	27 (13)	51 (11)	32 (7)
	Spring vetch	49 (15)	78 (16)	45 (13) b	29 (9)	33 (10)	26 (5)	100 (33)	24 (4)	62 (10)	27 (4)
H19	Fallow	33 (3)	59 (9)	32 (4) a	8 (3)	9 (4) a	14 (1) ab	159 (57)	10 (7)	38 (19)	8 (2)
	Winter rye	26 (8)	39 (6)	5 (1) b	6 (2)	6 (2) a	4 (1) a	198 (115)	11 (9)	52 (32)	7 (2)
	Saia oat	37 (12)	45 (7)	7 (1) bc	12 (8)	20 (7) b	14 (6) ab	220 (76)	7 (3)	48 (53)	5 (1)
	Spring vetch	40 (5)	51 (14)	10 (4) c	8 (6)	11 (3) a	16 (10) b	156 (40)	7 (2)	44 (34)	7 (6)
Mean	Fallow	49 (23)	84 (35)	83 (53) a	18 (17)	23 (19) ab	19 (7)	153 (92)	15 (14)	46 (21)	14 (10)
	Winter rye	46 (29)	67 (37)	14 (13) b	11 (9)	18 (14) a	14 (12)	177 (70)	10 (8)	44 (25)	8 (4)
	Saia oat	52 (27)	92 (72)	20 (16) b	20 (16)	45 (34) b	26 (20)	160 (68)	13 (11)	48 (32)	14 (11)
	Spring vetch	51 (23)	80 (36)	37 (24) b	19 (13)	29 (19) ab	27 (15)	173 (76)	14 (8)	48 (27)	13 (10)

Table S3. Mean topsoil mineral nitrogen (SMN) values across different cropping phases for the different treatments. Means (n=4 for individual trials, n=16 for averages across all site-years; except for rye in the sugar beet and winter wheat phases n=12) ± (SD). Significant differences among treatments within each phase are indicated by lowercase letters ($p<0.05$).

		SMN [kg N ha^{-1}]			
		Cover crop phase	Sugar beet phase	Winter wheat phase	Entire trial
G18	Fallow	80.5 (56.5) a	96 (72.5)	39.7 (22.5)	73.1 (58.1) a
	Winter rye	41.1 (33.2) b	89.3 (62.4)	35.9 (20.1)	51.4 (45) b
	Saia oat	64.9 (39.3) c	95.3 (61.5)	38.9 (23.9)	65.2 (46.9) a
	Spring vetch	74 (43.3) ac	106.5 (82.5)	41.5 (25.8)	73 (56.9) a
H18	Fallow	32.1 (21.8) a	41.9 (64.3)	14.3 (12)	31 (39.2)
	Winter rye	13.5 (18.5) b	55.3 (80.7)	13.5 (5.7)	25.6 (48.9)
	Saia oat	18.4 (15.3) b	47 (62)	13.5 (7.1)	25.6 (37.6)
	Spring vetch	27.2 (17.4) a	52.8 (67.6)	13 (7.5)	31.4 (41)
G19	Fallow	61.3 (36.3) a	56.5 (60.6)	39.7 (14)	54.1 (42.7)
	Winter rye	31.2 (14.8) b	89.4 (77.4)	55.1 (22.1)	55.9 (51.9)
	Saia oat	50.2 (45.8) a	61.9 (60.5)	45.9 (19.8)	52.8 (46.4)
	Spring vetch	44 (17.8) ab	59.8 (43.9)	50.9 (29.3)	50.8 (31.6)
H19	Fallow	26.9 (19) a	68.2 (94.4)	21.3 (14.2)	38.1 (57.6)
	Winter rye	14.3 (15.6) b	66.6 (66.9)	21.7 (17.1)	32.3 (45.5)
	Saia oat	19.8 (17.5) ab	68.3 (91.8)	19.7 (20.8)	34.7 (57.5)
	Spring vetch	22.5 (16.9) a	62.4 (58.3)	23.1 (19)	34.9 (39.8)
Mean	Fallow	48.3 (41.2) a	62.4 (75.8)	28.4 (19.4)	47.4 (51.8) a
	Winter rye	23.9 (24.3) b	67.7 (72.4)	23.3 (17.8)	34.6 (45.1) b
	Saia oat	36.4 (36.7) c	65.2 (72)	29.3 (23)	43 (49.6) c
	Spring vetch	40.4 (32.2) a	66.8 (65.1)	31.9 (26.4)	45.9 (45.4) ac

Table S4. Cumulative N_2O emissions across different cropping phases and entire trial (~18 months). Means (n=4 for individual trials, n=16 for averages across all site-years; except for rye in the sugar beet and winter wheat phases n=12) ± (SD). Significant differences among treatments within each phase are indicated by lowercase letters ($p<0.05$).

		N_2O-N [kg ha^{-1}]			
		Cover crop phase	Sugar beet phase	Winter wheat phase	Entire trial
G18	Fallow	0.41 (0.12) a	0.38 (0.14) ab	0.5 (0.13) ab	1.3 (0.32)
	Winter rye	0.46 (0.32) a	1.47 (1) b	0.25 (0.05) a	2.18 (1.34)
	Saia oat	1.5 (0.47) b	0.3 (0.21) a	0.76 (0.22) ab	2.56 (0.3)
	Spring vetch	0.58 (0.33) a	0.4 (0.11) ab	0.77 (0.41) b	1.76 (0.25)
H18	Fallow	0.11 (0.04) a	0.3 (0.22) a	1.43 (0.34)	1.85 (0.4) a
	Winter rye	0.22 (0.12) a	4.25 (3.12) b	0.78 (0.58)	5.24 (2.65) a
	Saia oat	0.67 (0.32) b	0.78 (0.25) a	1.6 (1.74)	3.05 (1.83) a
	Spring vetch	0.22 (0.16) a	0.49 (0.06) a	0.99 (0.55)	1.7 (0.6) b
G19	Fallow	0.44 (0.33) ab	0.76 (0.46)	1.85 (1.01)	3.06 (1.55)
	Winter rye	0.32 (0.04) a	2.94 (2.2)	1.95 (1.44)	5.21 (2.53)
	Saia oat	0.46 (0.18) ab	0.79 (0.18)	0.99 (0.38)	2.24 (0.33)
	Spring vetch	0.91 (0.34) b	1.01 (0.24)	0.73 (0.17)	2.65 (0.17)
H19	Fallow	0.18 (0.09)	0.55 (0.21) a	3.45 (2.3)	4.92 (2.16)
	Winter rye	0.19 (0.07)	4.59 (3.23) b	1.19 (0.98)	6.58 (4.92)
	Saia oat	0.46 (0.48)	0.37 (0.18) a	2.08 (1.99)	4.25 (4.63)
	Spring vetch	0.22 (0.12)	0.74 (0.46) a	5.18 (6.86)	6.59 (7.08)
Mean	Fallow	0.29 (0.22) a	0.5 (0.31) a	1.81 (1.58) a	2.6 (1.71)
	Winter rye	0.3 (0.19) ab	3.44 (2.81) b	0.74 (0.72) b	4.46 (2.98)
	Saia oat	0.78 (0.56) b	0.56 (0.3) a	1.36 (1.32) ab	2.69 (1.36)
	Spring vetch	0.49 (0.38) ab	0.66 (0.34) a	1.92 (3.65) a	3.07 (3.8)

Table S5. Fitted crop specific parameter to describe depth distribution of root carbon (C_w) for cover crops (equation 3, Gale und Grigal), derived total root carbon and share of root carbon in top soil on total root carbon

Cover crop	β	C_w 2018	C_w 2019	share of C_w in 0–20 cm [%]	share of C_w in 0 –30 cm [%]
Saia oat	0.95	0.34	0.23	64	79
Spring vetch	0.95	0.16	0.14	64	79
Winter rye	0.93	0.51	0.35	77	89

Table S6. Averaged carbon input (t C ha^{-1} a^{-1}) of the control scenario (no cover crops) for crop rotations CR1 and CR2

Crop rotation	Site	Cin_{shoot}	Cin_{root}	Cin_{fert}	Cin_{total}
CR1	Göttingen	2.57	1.42	0.16	4.15
CR2	Göttingen	3.08	1.44	0	4.51
CR1	Hohenheim	2.32	1.29	0.16	3.76
CR2	Hohenheim	2.83	1.32	0	4.15

Table S7. Averaged carbon input from cover crop residues in (t C ha^{-1}) for a profile depth of 0-30 cm.

Cin Variable	Cover crop	Göttingen	Hohenheim
Cin_{shoot}	Saia oat	0.94	0.96
Cin_{shoot}	Spring vetch	0.82	0.7
Cin_{shoot}	Winter rye	1.16	1.28
Cin_{root}	Saia oat	0.3	0.3
Cin_{root}	Spring vetch	0.14	0.12
Cin_{root}	Winter rye	0.5	0.54
Cin_{total}	Saia oat	1.24	1.26
Cin_{total}	Spring vetch	0.96	0.82
Cin_{total}	Winter rye	1.66	1.82

Cin_{shoot} Carbon input from above ground biomass, averaged measurements per site
Cin_{root} Carbon input of below ground biomass, based on root:shoot ratios
Cin_{total} Total carbon input

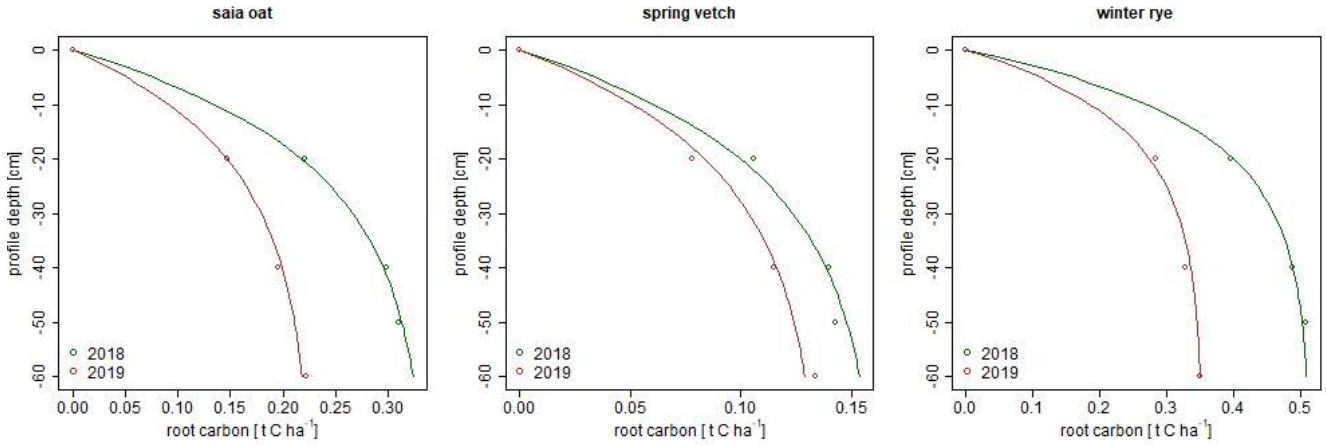

Figure S1. Accumulative depth distribution of root carbon for the Göttingen site. Fitted functions (equation 3, continuous lines) to describe the accumulative distribution of carbon in root biomass with depth using observed root carbon (points)