

Supplement of

Nutrient and dissolved organic carbon leaching in temperate alley-cropping agroforestry and open cropland

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Table S1. Site and climatic characteristics of alley-cropping agroforestry and open cropland on the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg) and clay Cambisol (Wendhausen).

Characteristics in the 0–0.3 m depth		Site				
Location	Vechta	Dornburg		Wendhausen		
	52°45' N, 8°32' E	51°00' N, 11°38' E		52°20' N, 10°37' E		
Soil type	Arenosol	Calcaric Phaeozem		Vertic Cambisol		
Texture (% sand-silt-clay)	80–13–7	6–66–28		21–40–39		
pH in 0–0.3 m	6.1 ± 0.1	7.1 ± 0.2		7.2 ± 0.2		
Total N (kg N m ⁻²) in 0–0.3 m	0.4 ± 0.0 kg m ⁻²	0.5 ± 0.0 kg m ⁻²		0.7 ± 0.0 kg m ⁻²		
Soil organic carbon (kg C m ⁻²) in 0–0.3 m	5.6 ± 0.4 kg m ⁻²	5.17 ± 0.20 kg m ⁻²		6.8 ± 0.4 kg m ⁻²		
Effective cation exchange capacity (mmol _c kg ⁻¹) in 0–0.3 m	36.5 ± 2.1	257.8 ± 44.3		351.6 ± 36.3		
Year of agroforestry establishment	2019	2007		2008		
Starting planting density	2222 trees ha ⁻¹	2222 trees ha ⁻¹		10000 trees ha ⁻¹		
Harvest of trees in agroforestry	None	01/2014		01/2013, 01/2021		
Total precipitation (mm) during the crop rotation	Silage corn (2019)	197	Spring barley (2019)	196	Silage corn (2019)	306
	Winter rye (2019–2020)	570	Fallow (2019–2020)	290	Fallow (2019–2020)	225
	Fallow (2020–2021)	246	Winter wheat (2020–2021)	663	Silage corn (2020)	212
	Potato (2021)	389	Winter barley (2021–2022)	356		
	Winter rye (2021–2022)	327				
Long-term mean annual precipitation (mm) 2012–2022	665 ± 36	556 ± 29		575 ± 36		
Annual precipitation during the study year (mm)	2019	625	450	505		
	2020	506	494	465		
	2021	503	698			
	2022	509	547			

Table S2. Soil parameters used in the Expert-N water sub-model for alley-cropping agroforestry (AF) and open cropland (OC) on the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg) and clay Cambisol (Wendhausen).

Soil type (site)	Soil parameters	AFtree	AFcrop 1m	AFcrop 7m	AFcrop 24m	OC
Sandy Arenosol (Vechta)	Porosity (vol %)	52				
	Field capacity (vol %)	41				
	Wilting point (vol %)	10.5				
	Saturated hydraulic conductivity (mm d ⁻¹)	528	588	588	522	585
	Van Genuchten α (cm ⁻¹)	0.06	0.05	0.03	0.05	0.04
	Van Genuchten n	1.66	1.82	1.82	1.63	1.78
Loam Phaeozem (Dornburg)	Porosity (vol %)	46.4				
	Field capacity (vol %)	41				
	Wilting point (vol %)	10.5				
	Saturated hydraulic conductivity (mm d ⁻¹)	400	364	298	298	98.6
	Van Genuchten α (cm ⁻¹)	0.039	0.052	0.052	0.053	0.102
	Van Genuchten n	1.35	1.34	1.33	1.33	1.29
Clay Cambisol (Wendhausen)	Porosity (vol %)	43.2				
	Field capacity (vol %)	46				
	Wilting point (vol %)	15.5				
	Saturated hydraulic conductivity (mm d ⁻¹)	297	142	224	224	224
	Van Genuchten α (cm ⁻¹)	0.129	0.17	0.19	0.146	0.206
	Van Genuchten n	1.16	1.2	1.19	1.19	1.19

Table S3. Mean leaching fluxes (\pm SE, $n = 4$) of NH_4^+ , NO_3^- , dissolved organic N (DON), dissolved organic C (DOC), and K ($\text{kg N, C, and K ha}^{-1}$) in alley-cropping agroforestry at 1 m, 7 m, and 24 m from the tree to the crop row on the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg) and clay Cambisol (Wendhausen).

Soil type (site)	Crop rotation	Distance within AFcrop	NH_4^+	NO_3^-	DON	DOC	K
Sandy Arenosol (Vechta)	Silage corn	1m	0.0 ± 0.0	0.9 ± 0.3	0.1 ± 0.0	0.4 ± 0.2	0.7 ± 0.3
	05/2019-	7m	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	09/2019	24m	0.0 ± 0.0	0.7 ± 0.5	0.1 ± 0.0	0.7 ± 0.4	1.4 ± 0.7
	Winter rye	1m	1.0 ± 0.8	61 ± 8.5	3.4 ± 0.6	45 ± 11	39 ± 6.1
	10/2019-	7m	0.3 ± 0.0	37 ± 28	1.9 ± 0.5	32 ± 11	13 ± 5.7
	08/2020	24m	1.5 ± 1.1	51 ± 18	4.3 ± 0.7	46 ± 17	37 ± 6.6
	Fallow	1m	0.1 ± 0.0	0.4 ± 0.2	1.0 ± 0.3	20 ± 4.9	5.6 ± 1.3
	09/2020-	7m	0.1 ± 0.0	0.5 ± 0.2	0.6 ± 0.3	14 ± 6.9	3.9 ± 1.9
	03/2021	24m	0.1 ± 0.0	1.3 ± 0.8	1.2 ± 0.5	22 ± 9.1	7.7 ± 3.5
	Potato	1m	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.1
	04/2021-	7m	0.0 ± 0.0	0.6 ± 0.5	0.0 ± 0.0	0.5 ± 0.4	0.7 ± 0.6
	10/2021	24m	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.1
	Winter rye	1m	0.1 ± 0.0	2.1 ± 1.4	0.4 ± 0.2	5.9 ± 3.8	4.0 ± 2.3
	11/2021-	7m	0.0 ± 0.0	1.6 ± 1.6	0.0 ± 0.0	1.6 ± 1.6	1.2 ± 1.2
07/2022	24m	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	
Loam Phaeozem (Dornburg)	Spring barley	1m	0.0 ± 0.0	0.7 ± 0.6	0.1 ± 0.0	0.6 ± 0.6	0.0 ± 0.0
	03/2019-	7m	0.0 ± 0.0	1.8 ± 1.8	0.1 ± 0.1	2.0 ± 2.0	0.0 ± 0.0
	07/2019	24m	0.0 ± 0.0	4.2 ± 1.4	0.1 ± 0.0	0.3 ± 0.2	0.0 ± 0.0
	Fallow	1m	0.0 ± 0.0	0.4 ± 0.4	0.0 ± 0.0	2.3 ± 1.4	0.2 ± 0.2
	08/2019-	7m	0.0 ± 0.0	1.7 ± 0.2	0.1 ± 0.0	4.0 ± 1.5	0.0 ± 0.0
	02/2020	24m	0.0 ± 0.0	0.9 ± 0.1	0.0 ± 0.0	0.5 ± 0.2	0.0 ± 0.0
	Winter wheat	1m	0.1 ± 0.0	2.5 ± 1.3	0.6 ± 0.2	33 ± 15	0.4 ± 0.2
	10/2020-	7m	0.3 ± 0.1	11 ± 3.5	0.7 ± 0.2	22 ± 7.6	0.4 ± 0.2
	08/2021	24m	0.1 ± 0.1	7.0 ± 5.4	0.5 ± 0.3	12 ± 8.0	0.2 ± 0.2
	Winter barley	1m	0.1 ± 0.0	0.1 ± 0.0	0.4 ± 0.1	47 ± 14	0.4 ± 0.1
10/2021-	7m	0.1 ± 0.0	1.4 ± 0.8	0.5 ± 0.3	46 ± 27	0.2 ± 0.2	
07/2022	24m	0.3 ± 0.2	9.7 ± 3.5	0.3 ± 0.3	21 ± 8.7	0.2 ± 0.2	
Clay Cambisol (Wendhausen)	Silage corn	1m	0.0 ± 0.0	0.6 ± 0.6	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	04/2019-	7m	0.0 ± 0.0	3.0 ± 1.9	0.1 ± 0.1	4.0 ± 4.0	0.1 ± 0.1
	10/2019	24m	0.0 ± 0.0	1.8 ± 1.8	0.2 ± 0.1	0.4 ± 0.4	0.2 ± 0.1
	Fallow	1m	0.3 ± 0.1	31 ± 18	1.0 ± 0.6	20 ± 10	0.8 ± 0.3
	11/2019-	7m	0.0 ± 0.0	3.0 ± 3.0	0.0 ± 0.0	1.3 ± 1.3	0.1 ± 0.1
	03/2020	24m	0.2 ± 0.1	24 ± 11	0.8 ± 0.3	14 ± 6.7	0.6 ± 0.4
	Silage corn	1m	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	04/2020-	7m	0.0 ± 0.0	7.7 ± 5.4	0.4 ± 0.2	6.3 ± 6.3	0.1 ± 0.1
	09/2020	24m	0.1 ± 0.0	8.9 ± 3.3	0.4 ± 0.2	32 ± 16	0.2 ± 0.1

Table S4. Statistical results from linear mixed-effects (LME) model evaluating the effect of management, i.e., alley-cropping agroforestry (AF, area-weighted between the tree row and the sampling distances within the crop row) vs. open cropland (OC) on z-transformed leaching fluxes of NO_3^- , dissolved organic nitrogen (DON), dissolved organic carbon (DOC), and K in each soil type (site). The LME model includes management system as a fixed effect and replicate plot and crop rotation as random effects; numerator degrees of freedom = 1; denominator degrees of freedom = 6.

Soil type (site)	Leaching fluxes	<i>F</i> value	<i>p</i> -value	<i>n</i> (AF or OC)
Sandy Arenosol (Vechta)	NO_3^-	5.01	0.07	20
	DON	2.24	0.19	20
	DOC	2.59	0.16	20
	K	7.44	0.03	20
Loam Phaeozem (Dornburg)	NO_3^-	3.62	0.11	16
	DON	2.43	0.17	16
	DOC	9.88	0.02	16
	K	5.99	0.99	16
Clay Cambisol (Wendhausen)	NO_3^-	0.058	0.81	12
	DON	1.02	0.35	12
	DOC	0.44	0.53	12
	K	0.59	0.47	12

Table S5. Mean (\pm SE, $n = 4$) above-ground crop N and C (g N and C m^{-2}) in alley-cropping agroforestry at 1 m, 7 m, and 24 m from the tree to the crop row (AFcrop) on the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg) and clay Cambisol (Wendhausen).

Soil type (site)	Crop rotation	Distance within AFcrop	Crop N (g N m^{-2})	Crop C (g C m^{-2})	
Sandy Arenosol (Vechta)	Silage corn 05/2019–09/2019	1m	27 \pm 2	966 \pm 102	
		7m	24 \pm 2	946 \pm 61	
		24m	28 \pm 3	1023 \pm 116	
	Winter rye 10/2019–08/2020	1m	5 \pm 0	189 \pm 13	
		7m	6 \pm 0	218 \pm 13	
		24m	7 \pm 0	224 \pm 8	
	Potato 04/2021–10/2021	1m	11 \pm 1	400 \pm 30	
		7m	13 \pm 1	443 \pm 12	
		24m	15 \pm 1	479 \pm 20	
	Winter rye 11/2021–07/2022	1m	7 \pm 0	237 \pm 13	
		7m	7 \pm 0	248 \pm 16	
		24m	9 \pm 0	279 \pm 16	
Loam Phaeozem (Dornburg)	Spring barley 03/2019–07/2019	1m	3 \pm 1	87 \pm 7	
		7m	8 \pm 0.2	207 \pm 3	
		24m	11 \pm 0.4	234 \pm 10	
	Winter wheat 10/2020–08/2021	1m	10 \pm 1	195 \pm 16	
		7m	15 \pm 1	297 \pm 16	
		24m	18 \pm 1	310 \pm 9	
	Winter barley 10/2021–07/2022	1m	6 \pm 1	196 \pm 18	
		7m	10 \pm 0	294 \pm 17	
		24m	10 \pm 0	307 \pm 9	
	Clay Cambisol (Wendhausen)	Silage corn 04/2019–10/2019	1m	1 \pm 0	21 \pm 11
			7m	14 \pm 2	510 \pm 73
			24m	18 \pm 1	695 \pm 15
Silage corn 04/2020– 09/2020		1m	1 \pm 0	36 \pm 6	
		7m	18 \pm 1	787 \pm 24	
		24m	19 \pm 1	875 \pm 43	

Table S6. Spearman's rank correlation coefficients (ρ) between leaching fluxes of NO_3^- , dissolved organic N (DON), dissolved organic C (DOC), and K with controlling factors for alley-cropping agroforestry tree row (AFtree), crop row (AFcrop), and open cropland (OC) across crop rotations and sites (* $0.08 > p > 0.05$, ** $p \leq 0.05$, * $p \leq 0.01$). Leaching fluxes are expressed as $\text{kg N, C or K ha}^{-1}$ per crop rotation or year (for AFtree); drainage flux and precipitation in mm per crop rotation; sand in percent; nitrogen uptake efficiency in kg crop-N kg^{-1} fertilizer-N.**

AFtree ($n = 44$)	Tree age	DOC leaching	DON leaching	K leaching	NO_3^- leaching	Drainage	Precipitation
DOC leaching	-0.74***						
DON leaching	-0.15***	0.50					
K leaching	-0.42***	0.70**	0.94***				
NO_3^- leaching	-0.80***	0.88***	0.56*	0.74**			
Drainage	0.06*	0.49	0.69**	0.63**	0.30		
Precipitation	0.14*	0.30	0.67**	0.56*	0.20	0.55*	
Sand content	-0.77***	0.77***	0.18***	0.40	0.68**	0.19	0.05

AFcrop ($n = 44$)	Tree age	DOC leaching	DON leaching	K leaching	NO_3^- leaching	Drainage	Precipitation	Sand content
DOC leaching	-0.29							
DON leaching	0.52*	0.1						
K leaching	-0.06	-0.04	0.63**					
NO_3^- leaching	-0.08	0.79***	0.01	-0.24				
Drainage	0.32	0.29	0.81***	0.76***	-0.15			
Precipitation	0.14	-0.20	0.43	0.74***	-0.24	0.55*		

Sand content	-0.77***	0.37	-0.32	0.31	0.19	-0.07	0.05	
Nitrogen uptake efficiency	-0.03	-0.47	-0.28	-0.62	0.28	-0.77	-0.50	-0.39

OC (n = 44)	DOC leaching	DON leaching	K leaching	NO ₃ ⁻ leaching	Drainage	Precipitation	Sand content
DON leaching	0.03						
K leaching	0.18	0.72***					
NO ₃ ⁻ leaching	0.52*	-0.16	0.24				
Drainage	0.39	0.77***	0.85***	0.10			
Precipitation	-0.26	0.48	0.60**	-0.23	0.47		
Sand content	0.57**	-0.21	0.22	0.25	0.12	-0.05	
Nitrogen uptake efficiency	-0.38	-0.43	-0.78**	0.08	-0.77**	-0.71**	-0.41

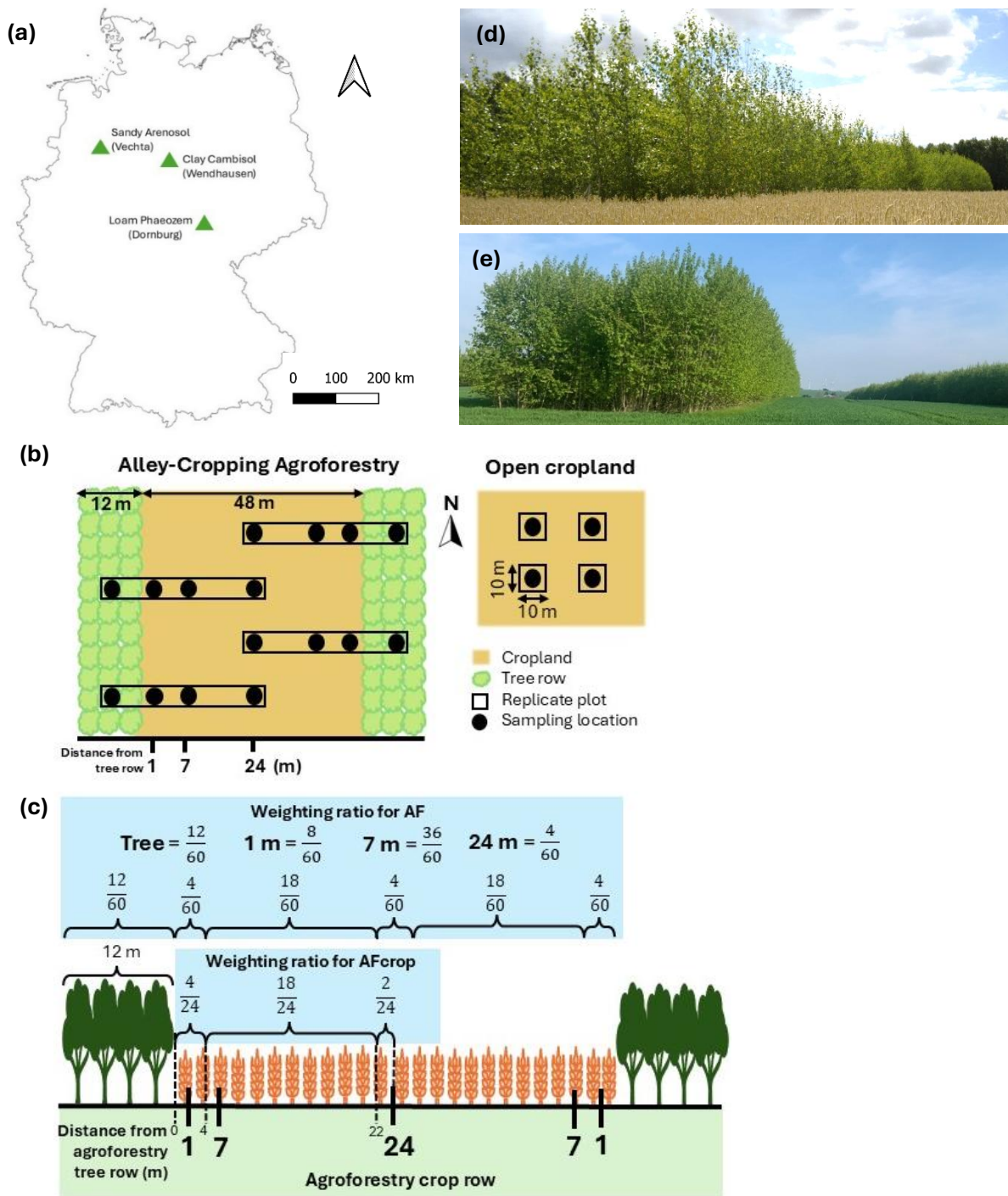


Figure S1. (a) Locations of the three study sites in Germany; (b) schematic representation of the sampling design in alley-cropping agroforestry (AF) and open cropland (OC); (c) the weighting factors used to calculate the area-weighted average for the overall AF (between the AF tree and AF crop rows) and weighted-average for the AF crop row; (d) AF with a 4-year-old poplar (*Populus nigra* × *P. maximowiczii*) on sandy Arenosol soil in Vechta (July 2022); (e) AF with an 8-year-old poplar on loam Phaeozem soil in Dornburg (April 2022). Photo credit: Sarah Choe.