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Dissolved organic carbon and nutrient leaching in temperate alley-cropping agroforestry and open cropland

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Abstract. Alley-cropping agroforestry with short-rotation coppice (AF) has been identified as a sustainable alternative to highly industrialised agricultural systems, enhancing ecosystem functions including the regulation of water quality. However, there is limited knowledge regarding the leaching of dissolved organic carbon (DOC) and nutrients in AF and treeless open cropland (OC). In this study, we compared the leaching of mineral nitrogen, dissolved organic nitrogen (DON), DOC, potassium, and phosphorus in AF tree rows (AFtree) and AF crop rows (AFcrop) with OC across three sites with different soil textures in Germany over four years (2019–2022). The objectives were to (1) quantify the fluxes of DOC and nutrients in AF and OC systems and (2) identify the primary drivers of leaching in both systems. At each site, we sampled soil-pore water from AFtree, AFcrop (at 1 m, 7 m, and 24 m from the AFtree) and OC monthly using suction cup lysimeters installed at 60-cm depth and analysed for DOC and nutrient concentrations. AFtree was unfertilised whereas AFcrop and OC had the same conventional fertilisation rates. Drainage fluxes were estimated using the Expert-N water sub-model. Our results showed that, in loam Phaeozem and clay Cambisol soils with mature AF (established for at least 12 years with ≥ 5-year-old AFtree in the second rotation), AFtree had N leaching of 0–0.5 kg N ha^{-1} yr^{-1} whereas OC had 1–4 kg N ha^{-1} cropping $period^{-1}$. Mature AF in the loam Phaeozem and clay Cambisol soils had two to 10 times lower NO_3^- leaching at 1 m than at 7 m and 24 m AFcrop. The effect of the AFtree on leaching was limited to ≤ 7 m AFcrop. Overall, AF (the area-weighted average of AFtree and AFcrop) did not differ from OC in DOC and nutrient leaching fluxes. An exception was observed in the sandy Arenosol soil during the first two years following AF establishment, when the overall AF exhibited higher NO_3^- and K leaching fluxes than OC, attributed to the large liquid manure application combined with soil disturbance from tree establishment and young tree roots. Across sites, precipitation and sand content were the dominant drivers of DOC and nutrient leaching in AFtree whereas precipitation was the only factor influencing leaching in AFcrop and OC. These results reinforce the importance of synchronising fertiliser input with the crop's demand in AFcrop as excessive fertilisation can override the tree root interception of nutrients at greater distances from the AFtree.

1 Introduction

Modern agricultural systems are often in a nutrient-saturated state, driven by the excessive application of fertilisers to achieve high productivity (Zhang et al., 2015). Nutrients that are not taken up by crops or retained in soils can be lost through various pathways, including leaching, which contributes to water pollution (Cameron et al., 2013). In 2022, approximately 16 % of groundwater monitoring sites in Germany exceeded the EU nitrate (NO_3^-) limit of 50 mg L^{-1} (Umweltbundesamt, 2024), with high concentrations found in agricultural regions (Cullmann et al., 2022). Although NO_3^- is the focus of agricultural leaching studies, dissolved organic nitrogen (DON) and carbon (DOC) also represent significant pathways of nutrient loss. DON can account for an average of 26 % of total soluble N leaching (Van Kessel et al., 2009; Zhang et al., 2025) while the decomposition of leaf litter and crop residues provide fresh inputs of organic C that enhance DOC leaching (Frouz et al., 2018). Moreover, DOC can influence NO_3^- concentrations in groundwater and surface waters by serving as an energy source for heterotrophic microbes (Hussain et al., 2020). The combined loss of inorganic and organic forms through leaching in the agricultural system emphasizes the need for management strategies that enhance nutrient retention and reduce leaching (Du et al., 2022).

Alley-cropping agroforestry with short rotation coppice (hereafter, AF), a land-use system in which rows of arable crops alternate with rows of fast-growing trees such as poplar (*Populus* spp.), is a sustainable alternative to highly industrialised agricultural systems that can reduce environmental degradation from soil nutrient leaching (Smith et al., 2013). AF provides a variety of ecosystem services, including improved water regulation (Pavlidis and Tsihrintzis, 2018; Mathieu et al., 2025) while maintaining comparable crop yields (Veldkamp et al., 2023). Specifically, the presence of agroforestry tree rows (hereafter, AFtree) has been reported to enhance water infiltration, retention, and storage capacities by decreasing soil bulk density and increasing soil porosity (Mitrová et al., 2025). The deep root systems in AFtree also play a crucial role in nutrient uptake by capturing nutrients that move below the rooting zone of adjacent crops (Bergeron et al., 2011). Initially, fine roots colonize the topsoil, but as AF systems mature, roots extend vertically and laterally into deeper soil layers, increasing the capacity of water storage (O'Connor et al., 2023). For example, in an AF system with fast-growing willow (*Salix viminalis*) in Sweden, NO_3^- leaching declined sharply from 341 kg N ha^{-1} in the first year to 3 kg N ha^{-1} in the second year (Aronsson and Bergström, 2001). Similarly, 10-year-old hybrid poplars exhibited 40–60 % lower nutrient leaching rates than younger trees in AFtree in Canada (Bergeron et al., 2011), highlighting that nutrient losses are reduced as AFtree stands mature.

Under similar climate conditions, soil texture is one of the major factors influencing nutrient leaching because it affects water infiltration, retention, and nutrient adsorption (Du et al., 2022). Coarse-textured (sandy) soils typically exhibit lower nutrient retention (i.e., low cation exchange capacity) and lower water-holding capacity than fine-textured (clay) soils. This results in faster downward movement of water and nutrients and higher leaching fluxes (Gaines and Gaines, 1994). In temperate agroecosystems, lower leaching fluxes have been observed in clay, silty, and loamy soils than in sandy soils due to their greater capacity to retain dissolved organic matter and nutrients (Dieser et al., 2023; Zhang et al., 2025). Conversely, sandy soils are more prone to leaching, because their large pores and weak adsorption capacity promote nutrient mobility, particularly under high rainfall or drainage conditions (Cameron et al., 2013). In a temperate AF study, soil clay content strongly influenced volumetric water content, which directly affected nitrate supply rates and subsurface leaching (Rivest and Martin–Guay, 2024). Similarly, lower leaching losses have been observed in clay soils than in sandy soils under irrigation in temperate AF systems (Aronsson and Bergström, 2001).

While coarse soil texture and high precipitation generally increase the risk of leaching (Huang and Hartemink, 2020), management practices such as fertilisation regime also have strong effects. When fertiliser applications exceed crop nutrient demand or are poorly timed, nutrients accumulate in the topsoil and become susceptible to leaching (Lu et al., 2019). Conversely, synchronising fertiliser application with crop nutrient uptake can minimize losses even under high rainfall (Dieser et al., 2023). In AF systems, particularly within AFtree, fertiliser inputs can be reduced through nutrient recycling via litterfall decomposition. This process sustains internal nutrient cycling and mitigates leaching risks (Puget and Drinkwater, 2001) as compared to treeless open croplands (hereafter, OC). Furthermore, AFtree influences the spatial patterns of leaching in adjacent crop rows (hereafter, AFcrop). A recent study of temperate AF in Canada reported that NO_3^- leaching near AFtree was approximately nine times lower than at locations farther away, due to lower soil volumetric water content resulting from greater interception and uptake by trees (Rivest and Martin–Guay, 2024). However, in our earlier study, we observed reduced yields of spring crops at 1–4 m distance from the AFtree aged ≥ 5 years, which may increase the risk of nutrient leaching due to reduced nutrient uptake by crops. Collectively, these findings underscore the combined influence of soil texture, precipitation, drainage, and crop uptake as primary drivers of nutrient leaching in temperate AF systems (Zhu et al., 2020).

Despite the growing body of research on the effects of AF systems on nutrient leaching, there is a lack of empirical studies quantifying the leaching of nutrients and DOC across AF sites with varying AF maturity and soil texture in temperate regions. In this study, we present data on NO_3^-, DON, DOC and K leaching losses obtained using a replicated design that compared AF and adjacent OC systems across different soil texture over a four-year period (2019–2022). Our objectives were to (1) quantify dissolved organic carbon and nutrient leaching fluxes in AF and OC systems, and (2) identify the primary drivers of leaching in AFtree, AFcrop, and OC. We hypothesised that (1) within the same crop growing season, dissolved organic carbon and nutrient leaching will be greater in OC than in AF systems and (2) nutrient leaching fluxes across sites will be influenced by tree age, sand content, precipitation, and nutrient uptake efficiency (i.e. amounts of nutrients taken up by the crops ratioed to fertilisation rates).

2 Materials and Methods

2.1 Study sites and experimental design

This study was conducted at three sites that encompassed a soil texture gradient (Table S1): sandy Arenosol (Vechta), loam Calcaric Phaeozem (Dornburg), and clay Vertic Cambisol (Wendhausen) soils, all located in central Germany (Fig. S1a). Measurements of soil-pore water were carried out from 2019–2022 in Vechta and Dornburg sites and from 2019–2020 in Wendhausen site. The soil characteristics, years since AFtree establishment and coppicing, crop rotations, and climatic characteristics are provided in Table S1. Hereafter, each site is referred to by its soil type.

The AF system on the sandy Arenosol soil was established in 2019 and represented an early-stage AF, whereas those on the loam Phaeozem and clay Cambisol soils were established in 2007–2008 and represented mature AF systems. All three sites shared an identical AF design, consisting of alternating 12 m wide poplar (*P. nigra* × *P. maximowiczii*; clone Max 1) rows with 24 m wide crop alleys on each side of the tree row. Each AF plot, established on former OC, was paired with an adjacent OC plot (Fig. S1b). Crop rotations, fertilisation dates and rates, and crop sowing and harvesting schedules (Table 1) were identical for AFcrop and OC at each site. The AFtree rows were not fertilised, and both roots and branches were left unpruned. Trees were coppiced at different intervals in each site according to farmers' practice; on each coppicing, they were cut close to the ground and trees resprouted. In this study, *tree age in rotation* refers to the number of years within a single rotation cycle, defined as the period between two successive coppicing events (Table 2). *Year since establishment* refers to the start when AFtree was planted (Table 2).

Table 1: Management practices in alley-cropping agroforestry and open cropland on the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg) and clay Cambisol (Wendhausen).

Soil type (site)	Crop rotation	Sowing/ onset	Harvest/ cessation	Fertilisation date	Fertilisation rate (kg N-P-K ha^{-1} yr^{-1})
Sandy Arenosol (Vechta)	Silage corn	2019-05-03	2019-09-20	2019-04-24	120-40-62 Liquid manure
				2019-05-03	33-14-0 Mineral fertiliser
	Winter rye	2019-10-03	2020-08-06	2020-03-06	120-30-131 Liquid manure
				2020-03-19	60-0-0 Urea
	Fallow	2020-08-07	2021-04-08	2020-08-14	37-3-22 Liquid manure
	Potato	2021-04-09	2021-10-21	2021-03-17	63-9-61 Fermentation residues
				2021-04-06	68-40-75 Mineral fertiliser
	Winter rye	2021-11-03	2022-07-28	2022-03-18	178-25-65 Liquid manure
Loam Phaeozem (Dornburg)	Spring barley	2019-03-05	2019-07-22	2019-04-01	36-22-31 Mineral fertiliser
	Fallow	2019-07-23	2020-03-27	-	-
	Spring barley	2020-03-28	2020-08-12	2020-03-31	45-20-37 Mineral fertiliser
	Winter wheat	2020-10-28	2021-08-21	2021-03-26	120-0-0 Mineral fertiliser

	Winter barley	2021-10-02	2022-07-16	2022-03-21	152-0-0 Mineral fertiliser
Clay Cambisol (Wendhausen)	Silage corn	2019-04-18	2019-10-23	2019-05-07	101-0-0 Urea
	Fallow	2019-10-24	2020-04-20	2020-04-20	28-33-0 Mineral fertiliser
	Silage corn	2020-04-21	2020-09-28	2020-04-28	120-0-0 Mineral fertiliser

2.2 Soil element leaching measurement

2.2.1 Soil-pore water sampling

Soil-pore water was sampled using P80 ceramic suction-cup lysimeters (CeramTec AG, Marktredwitz, Germany; maximum pore diameter 1 µm). At each site, there were four replicate plots in the AF and four replicate plots in the OC (Fig. S1b). In each replicate plot of the AF, suction-cup lysimeters were installed within the AFtree and at three distances within the AFcrop: 1 m, 7 m, and 24 m from the AFtree. In the OC, the four lysimeters were placed at the centre of each 10 × 10 m replicate plot. In total, there were 20 lysimeters at each site. The lysimeters were inserted into the soil down to 0.6 m depth so that the soil-pore water was collected beyond the crops' main rooting depth. Soil water was extracted by applying a 60 kPa vacuum to each lysimeter tube and conveyed via plastic tube into dark glass bottles, which were sealed and stored in a lidded container in the shade of the tree row. Subsequently, soil-pore water samples were transferred into pre-rinsed 100 ml plastic bottles and stored at −25° C until analysis. From April to September (mean precipitation < 50 mm month^{-1}; Fig. 1), soil-pore-water remained lower than from October to March (mean precipitation > 50 mm month^{-1}; Fig. 1), and thus sampling was conducted 1–2 times between April to September and 4–6 times between October to March. Lysimeters were temporarily removed during the summer harvest to facilitate machinery access.

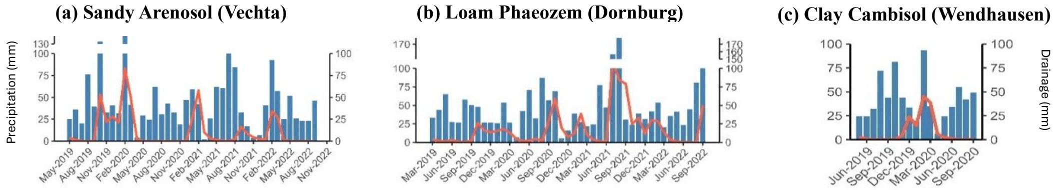
(a) Sandy Arenosol (Vechta)
(b) Loam Phaeozem (Dornburg)
(c) Clay Cambisol (Wendhausen)

Figure 1*:* **Monthly water drainage fluxes in alley-cropping agroforestry crop row at 0.6-m depth (mm month^{-1}), simulated by Expert-N water sub-model (red line), and monthly precipitation (mm month^{-1}; blue bars) from 2019–2022 in the three soil types: (a) sandy Arenosol, (b) loam Phaeozem, and (c) clay Cambisol.**

2.2.2 Quantifying element concentration

Total dissolved N (TDN), NH_4^+, and NO_3^- were determined by continuous-flow injection colorimetry on an AA3 autoanalyzer (SEAL Analytical GmbH, Norderstedt, Germany). TDN was quantified following UV-persulfate digestion and hydrazine-sulfate reduction (autoanalyzer method G-157-96), NH_4^+ via the salicylate–dichloroisocyanurate reaction (G-102-93), and NO_3^- by cadmium reduction with NH_4Cl buffer (G-254-02). Dissolved organic N (DON) was calculated as the difference between TDN and the sum of NH_4^+ and NO_3^-. Dissolved organic C (DOC) was measured on a TOC–VWP analyzer (Shimadzu Europa GmbH, Duisburg, Germany) after acidification with H_3PO_4 to remove inorganic carbon and UV-persulfate oxidation of organic C to CO_2, which was detected by infrared analysis. Dissolved K and total P were measured using an inductively coupled plasma–optical emission spectrometer (ICP-OES; iCAP 6300, Thermo Fischer Scientific GmbH, Dreieich, Germany).

2.2.3 Soil water modelling and element leaching flux calculation

Drainage fluxes were estimated using the water sub-model of Expert-N v5.0 (Priesack, 2005), as shown in our previous works in various land-use systems (Kurniawan et al., 2018; Formaglio et al., 2020) including temperate alley-cropping agroforestry (Veldkamp et al., 2023). The model was parameterised with site characteristics (Tables S1) and vegetation characteristics (e.g., tree and crop biomass; Choe et al., 2025), measured on AF and OC in the study sites. The input climate data were daily air temperature, relative humidity, solar radiation, wind speed, and precipitation, recorded using an eddy-covariance mast placed in AFtree and OC at each site (Markwitz et al., 2020). The soil properties (texture, bulk density, pH, and soil organic C), determined in the 0–0.3 m soil depth in AFtree, AFcrop (1 m, 7 m, and 24 m) and OC, were used in pedotransfer functions to derive soil parameters used in the Expert-N water sub-model (Table S2).

Daily drainage fluxes were simulated as follows:

$$D = P - (ET + R + \Delta S) \tag{1}$$

where P is precipitation; ET is evapotranspiration – partitioned into canopy interception, actual soil evaporation and plant transpiration via the Penman–Monteith equation (Allen et al., 1998); R is surface runoff; and ΔS is the change in soil water storage (Kurniawan et al., 2018; Formaglio et al., 2020). Model performance was validated by comparing simulated soil matric potential against field measurements from P80 ceramic tensiometers (CeramTec AG; 1 µm pore size) installed at 0.6 m depth adjacent to each plot's lysimeter.

For calculating element leaching fluxes (mg m^{-2}), the measured solute concentrations (mg L^{-1}) in soil-pore water were multiplied by the cumulative drainage fluxes (L m^{-2}), for a given sampling period. Element leaching fluxes during a specified crop rotation or in a year was the sum of the element leaching fluxes for that period in kg ha^{-1}. When leaching fluxes are reported for the AFcrop, the sampling distances (1 m, 7 m, and 24 m) were area-weighted to get a value for each replicate plot (Fig. S1c). When leaching fluxes are reported for the whole AF, AFcrop was weighted by 0.8 and AFtree was weighted by 0.2, representing their respective areal coverages in each AF replicate plot (Fig. S1c).

2.3 Leaching driving factors

AFtree age, soil texture (% sand), fertilisation rates, crops' nutrient uptake efficiency (NUpE), precipitation, and drainage fluxes were used to explore potential drivers of leaching fluxes in AFtree, AFcrop, and OC. The three study sites spanned AFtree ages of 1–4 years in the sandy Arenosol soil, 5–8 years in the loam Phaeozem soil, and from 6–7 years in the clay Cambisol soil (Table 2). The AFtree age specifically refers to the age during a single coppice rotation cycle, defined as the period from one cutting to the next. Soil particle size distribution (i.e., % sand) was analysed in the top 0.3 m depth, using the pipette method (Table S1; Gee and Bouder, 1986). Crop NUpE (kg N kg^{-1} N-fertiliser) was calculated following (Moll et al., 1982): (nutrient concentration, kg N kg^{-1} plant biomass) × (plant biomass production, kg ha^{-1}) ÷ (N fertilisation rate, kg N ha^{-1}). NUpE serves as an index of nutrient synchronisation of nutrient uptake and fertiliser input, with lower values indicating low synchronisation in amounts and therefore high potential for nutrient leaching (Bohman et al., 2021). For calculating the NUpE, aboveground crop biomass and yield were determined at each sampling distance in the AFcrop replicate plot and within 10 m × 10 m harvest area of each OC plot (Fig. S1b). The plant samples were oven-dried at 60° C until constant dry matter weight. N concentrations in crops' biomass and yield were determined from oven-dried and ground samples, using a CN analyser (Elementar Vario EL; Elementar Analysis Systems GmbH, Hanau, Germany).

Total precipitation (mm) during the crop rotation was the sum of the daily rainfall from the start to the end of each crop rotation (Table S1). For the long-term average precipitation (Table S1), data were retrieved from the nearest German weather stations: station ID 963 for sandy Arenosol (Vechta), station ID 2444 for loam Phaeozem (Dornburg), and station ID 662 for clay Cambisol (Wendhausen) (Deutscher Wetterdienst, 2020).

For quantifying the nutrient inputs from the AFtree leaf litter, baskets with 0.14 m^2 surface area were placed in the AFtree and AFcrop (1 m, 7 m, 24 m) from September until complete leaf fall. Collected leaf litter was oven-dried at 60 °C to constant weight and ground for chemical analysis. The N and C concentrations in the leaf litter were determined using a CN analyser while P and K concentrations were determined by pressure digestion of plant samples in concentrated HNO_3 and the digests were analysed using ICP-OES as described above. Nutrient input (kg N, P or K ha^{-1}) was the product of leaf litter mass ha^{-1} and its nutrient concentration.

2.4 Statistical analyses

To reveal spatial pattern of leaching fluxes from the AFtree to various distances (1 m, 7 m, 24 m) within the AFcrop (Fig. 2), we expressed the leaching fluxes as the ratio to the OC for each soil type (site) during each crop rotation:

$$Leaching\ ratio = \frac{leaching\ flux\ of\ AF\ replicate\ plot}{mean\ leaching\ flux\ of\ OC} \quad (2)$$

where the denominator is the mean of four replicate plots in OC at each soil type (site) for each crop rotation. We used a non-parametric bootstrap resampling with10,000 iterations (Powers et al., 2011; Veldkamp et al., 2020) to estimate the 95 % confidence intervals (CI). When the CI crosses 1 (i.e., the mean of OC), the leaching fluxes in AFtree, the various AFcrop distances, or overall AF (area-weighted average between AFtree and AFcrop) were considered not significantly different from OC ($p > 0.05$).

For comparison between AF and OC, it is important that some of the high leaching fluxes should not disproportionately skew the statistical data distribution. The z-transformation has been used in many studies on soil and ecosystem functions whereby different indicators with wide ranging magnitudes are used to assess differences between treatments, and those indicators with large magnitudes are not dominating but that all indicators are equally considered into the statistical analysis (e.g., Iddris et al., 2023; Veldkamp et al., 2023). Thus, for comparison between overall AF (area-weighted between AFtree and AFcrop sampling distances) and OC, we applied a z-transformation. Leaching fluxes were standardised as: z = (replicate plot value − overall mean of AF and OC in the same soil type and crop rotation) ÷ standard deviation. We then used the z-transformed values to analyse differences between AF and OC across crop rotations. This was assessed by linear mixed-effects (LME) model with management system as a fixed effect and replicate plot and crop rotation as random effects (Table S4).

Spearman's rank correlation was conducted separately for AFtree, AFcrop, and OC to examine the relationships between leaching fluxes and controlling factors across soil types and crop rotations. For this analysis, the leaching fluxes are expressed as kg N, C or K ha^{-1} per crop rotation; drainage flux and precipitation are in mm per crop rotation; soil texture is represented by percent sand; NUpE is in kg crop-N kg^{-1} N-fertiliser. The NH_4^+ and P leaching fluxes were negligible and hence it was not relevant to assess their relationship with controlling factors. To assess the combined influence of controlling factors on NO_3^-, DOC, DON, and K fluxes, we performed stepwise linear regression, including only the factors that exhibit non-collinearity and are the most fitting predictors based on the R^2. For this analysis, we use the mean value of four replicate plots on each crop rotation, and regression analysis was conducted across soil types and crop rotations; the units of leaching fluxes and controlling factors are the same as above. This regression analysis is aimed to refine predictive models applicable to the ranges of soil and crop types as well as climatic conditions covered in our study. Statistical significance was considered at $p \leq 0.05$. All analyses were conducted using R version 4.3.3 (R Core Team, 2024).

3 Results

3.1 Leaching fluxes in alley-cropping agroforestry compared to open cropland

In the sandy Arenosol soil, where AFtree was only 1–4 years old (Table 2), the leaching fluxes of NO_3^-, DON, DOC, and K were higher in AFtree than in OC, as indicated by the 95 % CI exceeding 1 (Fig. 2a–d). The unfertilised AFtree showed high leaching fluxes of NO_3^-, K and DOC during the first two years following AF establishment (Table 2), coinciding with the large application of liquid manure followed by mineral N fertilisers in the adjacent AFcrop (Table 1). By the fourth year of

AF establishment, NO_3^- leaching fluxes declined from 76 to 0.4 kg N ha^{-1} yr^{-1}, accounting 97 % of dissolved N at a tree age of one year to only 20 % at a tree age of four years; K leaching fluxes also declined from 18 to 5 kg K ha^{-1} yr^{-1} (Table 2). Similarly, the various distances within the fertilised AFcrop had comparable NO_3^- and K leaching fluxes (37–61 kg N and 13–39 kg K ha^{-1} during October 2019–August 2020 cropping period for winter rye; Table S3) to the fertilised OC (36 kg N and 15 kg K ha^{-1} during the same cropping period; Table 3), following the large liquid manure application during the first two years of AF establishment (Table 1). During the third and fourth year of AF establishment, the leaching of DOC and nutrients in the AFcrop were 89–95 % lower than in the first two years but still were comparable to the OC (Table 3).

On contrary, in the loam Phaeozem and clay Cambisol soils, 12–16 years since AF establishment with 5–8-year-old AFtree in the second rotation, N leaching in the unfertilised AFtree (0–0.5 kg N ha^{-1} yr^{-1}; Table 2; Fig. 2i, j) were lower than the fertilised OC (1–5 kg N ha^{-1} cropping period^{-1}; Table 3). The various distances within the fertilised AFcrop showed comparable leaching fluxes to the OC (Fig. 2f, h–l), except in two cases in the loam Phaeozem: higher NO_3^- leaching in AFcrop at 7 m and 24 m (Fig. 2e; 1–11 kg N ha^{-1} cropping period^{-1}; Table S3), and the higher DOC leaching in AFcrop at 1 m and 7 m (Fig. 2g; 22–47 kg C ha^{-1} cropping period^{-1}; Table S3) than in OC (Table 3).

When comparing leaching fluxes between the overall AF (area-weighted average of AFtree and AFcrop) and OC across crop rotations for each site (Fig. 3), AF and OC only differed in two cases (Table S4): DOC leaching fluxes were higher in AF than in OC in the loam Phaeozem soil ($p = 0.02$, Fig. 3c), and K leaching fluxes were higher in AF than in OC in the sandy Arenosol soil ($p = 0.03$, Fig. 3d). The NO_3^- leaching was only marginally greater in AF than in OC in the sandy Arenosol soil ($p = 0.07$, Fig 3a; Table S4).

Across all sites and years, NH_4^+ leaching (0– 0.5 kg N ha^{-1} cropping period^{-1}; Table 3) and dissolved P leaching were negligible with one exception in OC on sandy Arenosol soil during large liquid manure application to winter rye (0–5 kg P ha^{-1} cropping period^{-1}; Table 3).

3.2 Drivers of leaching fluxes in alley-cropping agroforestry and open cropland

At all sites, monthly precipitation and drainage fluxes (Fig. 1) were greater from October to March, during fallow period or slow vegetative growth of winter crops, than from April to September during crops' full vegetative growth till harvest. In the sandy Arenosol soil (Fig. 1a), monthly drainage fluxes peaked between October 2019 and February 2020 (winter rye) and between December 2020 and February 2021 (fallow). In the loam Phaeozem soil (Fig. 1b), drainage fluxes were high between October 2019 and February 2020 (fallow), between October 2020 and February 2021 (winter wheat), and between October 2021 and February 2022 (winter barley). In the clay Cambisol soil (Fig. 1c), peak drainage fluxes occurred between December 2019 and March 2020 (fallow).

As nutrient demands vary among crops, fertilisation rates (Table 1) and the amount of N taken up by the crops' above-ground biomass (Table S5) also differed depending on the crop types. The average NUpE (i.e., ratio of crop N uptake to N fertiliser rate; Table 3) was 1.36 ± 0.11 across all crop rotations. The high NUpE was observed for spring barley grown on loam Phaeozem soil (3.33 ± 0.32) and silage corn grown on sandy Arenosol soil (1.51 ± 0.09) whereas winter barley on loam Phaeozem soil (0.70 ± 0.04) and winter rye on sandy Arenosol soil (0.48 ± 0.27) exhibited the low NUpE.

For AFtree, among the factors tested for correlations (Table S6), the sand content and precipitation were the strongest predictors of NO_3^-, DON, K and DOC leaching fluxes (Table 4). Tree age was correlated with these leaching fluxes but was excluded from the regression models due to its multicollinearity with sand content and precipitation (Table S6). The sand content and precipitation were the best predictors without multicollinearity with other independent variables, explaining 39–86 % of the variations in leaching fluxes across sites and years (Table 4). For AFcrop and OC, precipitation was the only factor significantly predicting DON and K leaching losses, explaining 26–64 % of the variation across sites and crop rotations (Table 4). There were no other significant correlations observed between leaching fluxes and the factors tested (Table S6).

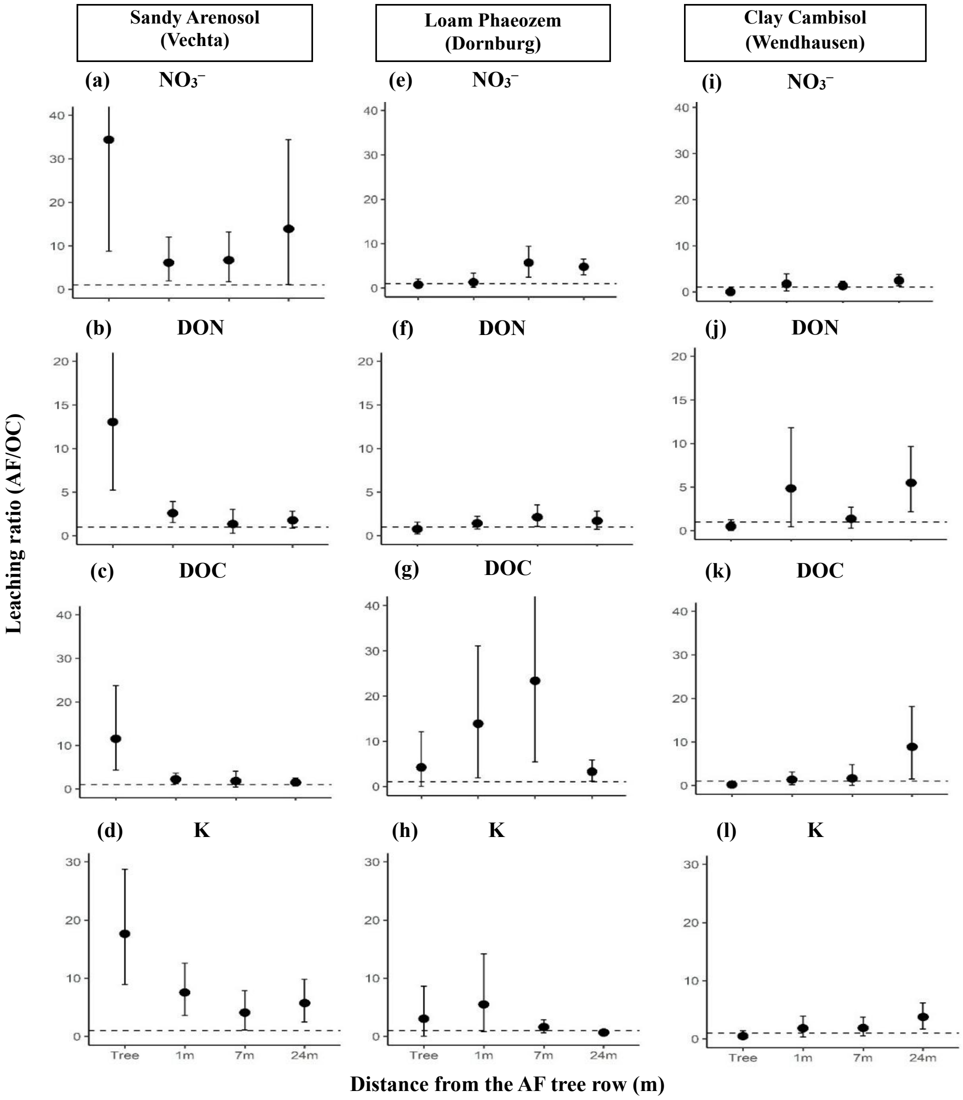

Figure 2: Ratio of leaching fluxes of nitrate (NO_3^-), dissolved organic nitrogen (DON), dissolved organic carbon (DOC), and potassium (K) in alley-cropping agroforestry (AF) tree row (Tree) and at 1 m, 7 m, and 24 m within the AF crop row relative to the open cropland (OC), calculated as e.g., tree or 1 m ÷ mean OC; leaching flux is summed over the crop rotation period. Results are presented across crop rotations for each soil type: sandy Arenosol (n = 4 plots × 5 rotations = 20), loam Phaeozem (n = 4 plots × 4 rotations = 16), and clay Cambisol (n = 4 plots × 3 rotations = 12). Data points show the means ± 95 % confidence intervals (CI). The dashed line indicates 1; when the 95 % CI crosses 1, leaching fluxes do not differ significantly from OC ($p > 0.05$).

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Table 2: Annual means (± SE; n = 4) of leaching fluxes and leaf litter inputs of N, P, K and C (kg N, P, K, and C ha^{-1} yr^{-1}) in the alley-cropping agroforestry tree row on the three soil types: sandy Arenosol, loam Phaeozem, and clay Cambisol.

Soil type (site)	Sandy Arenosol (Vechta)				Loam Phaeozem (Dornburg)				Clay Cambisol (Wendhausen)	
Study year	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020
Tree age in rotation	1	2	3	4	5	6	7	8	6	7
Year since establishment	1	2	3	4	13	14	15	16	12	13
Leaf litter N	0	0.9 ± 0	3 ± 1	2 ± 0.4	1 ± 0.1	0.8 ± 0.1	1 ± 0.1	2 ± 0.4	2 ± 0.3	3 ± 0.1
Total N leaching:	78 ± 12	28 ± 7	4 ± 1	2 ± 1	0	0.5 ± 0.2	0.4 ± 0.2	0	0.2 ± 0.1	0.1 ± 0.1
NO_3^-	76 ± 12	26 ± 7	3 ± 1	0.4 ± 0.4	0	0.3 ± 0.2	0.2 ± 0.2	0	0.1 ± 0.1	0
NH_4^+	0.1 ± 0	0.2 ± 0	0.1 ± 0	0.1 ± 0	0	0.1 ± 0	0	0	0	0
DON	2 ± 0.3	2 ± 0.2	0.8 ± 0.2	1 ± 0.7	0	0.1 ± 0	0.2 ± 0.1	0	0.1 ± 0	0.1 ± 0.1
Leaf litter P	0	0.2 ± 0	0.5 ± 0.2	0.6 ± 0.1	0.2 ± 0	0.1 ± 0	0.2 ± 0	0.6 ± 0.1	0.5 ± 0.1	1 ± 0.1
P leaching	0	0	0	0	0	0	0	0	0	0
Leaf litter K	0	0.7 ± 0	2 ± 0.5	2 ± 0.3	0.8 ± 0.1	0.5 ± 0	0.6 ± 0	2 ± 0.4	1 ± 0.4	3 ± 0.3
K leaching	18 ± 3	16 ± 2	8 ± 3	5 ± 2	0	0.1 ± 0.1	0.1 ± 0.1	0	0	0.2 ± 0.2
Leaf litter C	0	45 ± 1	101 ± 32	111 ± 19	49 ± 4	33 ± 2	33 ± 1	102 ± 22	78 ± 22	142 ± 17
DOC leaching	10 ± 1	23 ± 4	17 ± 5	12 ± 3	0	0.7 ± 0.7	15 ± 12	0.6 ± 0.6	7 ± 3	3 ± 2

4 Discussion

4.1 Leaching dynamics in agroforestry tree rows and their controlling factors

In the sandy Arenosol soil, high leaching of NO_3^- and K in AFtree (Table 2) during the first two years (2019–2020) was possibly due to soil disturbance during AF establishment, shallow roots of the newly established AFtree, lateral leaching from excessive N and K fertilisation rates in the adjacent AFcrop (Table 1), and the inherent soil properties with near neutral pH (i.e. negligible positive-charge surfaces) and low ECEC (Table S1), facilitating the rapid movement of the mobile NO_3^- and K^+ ions from the liquid manure and mineral fertiliser applied in the adjacent AFcrop. Soil disturbance during the establishment of AFtree likely increased leaching by compacting deeper soil layer and disrupting aggregate structure (Goodlass et al., 2007; Wolz et al., 2018), which may have facilitated lateral flow from the fertilised adjacent AFcrop into the AFtree. The shallow roots of newly established AFtree would be inadequate to intercept these leached ions. Additionally, residual effects from previous fertilisers of the preceding crops prior to AF conversion may also have contributed to the high leaching fluxes (Lehmann and Schroth, 2002; O'Connor et al., 2023). Similarly, the spring applications of liquid manure (Table 1), typically rich in organic C (Gross and Glaser, 2021), and the occurrence of high rainfall and drainage fluxes during spring and fallow periods (Fig. 1a) likely caused the large DOC leaching in 2020 and 2021 (Table 2). However, by the fourth year, NO_3^- leaching in the AFtree on Arenosol soil had declined to negligible levels whereas K leaching was four times lower than in the first year (Table 2), in line with the findings of Goodlass et al. (2007). This reduction was likely driven by the cessation of fertilisation in AFtree, the gradual depletion of residual fertilisers from previous agricultural use (Mortensen et al., 1998), and the expansion of tree roots capable of absorbing deeper leachate as the trees matured. This was also evident in the loam Phaeozem and clay Cambisol soils, 12–16 years since AFtree establishment with 5–8-year-old AFtree in the second rotation, whereby N and K leaching fluxes in AFtree were near zero (Table 2). In a fertilised poplar plantation in Germany, up to 82 % of the N input was initially lost, but these losses declined with increasing fine-root biomass (Kern et al., 2018). Over time, fast-growing, water-demanding species such as poplars can reduce leaching as their roots mature. While young trees primarily establish roots in the topsoil (0–30 cm), trees older than five years develop root systems that expand to depths of > 2 m (O'Connor et al., 2023). The impact of roots on soil moisture is further supported by lower soil moisture content within AFtree during all growth stages compared to croplands (Clivot et al., 2020; Judson et al., 2025), and the significant increase of topsoil water content following root pruning (Hébert et al., 2024). In the present study, the significant negative correlations of nutrient and DOC leaching fluxes with tree age across soil types (Table S6) underscored the effect of maturing trees in mitigating leaching.

The controls of soil texture and precipitation on nutrient (NO_3^-, DON and K) and DOC leaching in AFtree (Table 4) signified their influence on sorption capacity and drainage flux. Coarse-textured soils under high precipitation are more prone to leaching due to the presence of macropores and low solute adsorption compared with fine-textured soils (Gaines and Gaines, 1994; Soriano–Disla et al., 2012; Lu et al., 2019). The low clay content and low ECEC of the sandy Arenosol soil (Table S1) resulted in low adsorption for a highly mobile K^+ and hence higher leaching compared to the finer-textured Phaeozem and Cambisol soils. For mobile NO_3^- and anionic organic solutes (DON and DOC), the soils' pH of 6–7 suggest negligible positive-charge surfaces and thus unlikely to adsorb anions via cationic bridges (Guggenberger and Kaiser, 2003). Accordingly, poplar roots were less effective at reducing NO_3^- leaching in coarse-textured soils than finer-textured soils for Canadian AF systems (Bergeron et al., 2011). These findings imply that in the coarse-textured soils especially during the early years of AFtree establishment, when soil disturbance from tree establishment can facilitate lateral transfer from the fertilised AFcrop, leaching losses can be mitigated by growing low nutrient demand crops (e.g., winter rye or spring barley with lower crop N demand than silage corn or winter wheat; Table 3) to warrant low fertilisation rate in the adjacent AFcrop and consequently reduce lateral transfer into the young AFtree.

Table 3: Annual nitrogen deposition (Umweltbundesamt, 2018), fertilisation rate, and means (± SE; n = 4) of above-ground crop N and C and leaching fluxes (kg N, P, K, and C ha^{-1} cropping period^{-1}) in alley-cropping agroforestry crop row (AFcrop) and open cropland (OC) on the three soil types: sandy Arenosol, loam Phaeozem, and clay Cambisol.

Soil type (site)	Sandy Arenosol (Vechta)									
Crop rotation (date)	Silage corn 05/2019-09/2019		Winter rye 10/2019-08/2020		Fallow 09/2020-03/2021		Potato 04/2021-10/2021		Winter rye 11/2021-07/2022	
Management	AFcrop	OC	AFcrop	OC	AFcrop	OC	AFcrop	OC	AFcrop	OC
N deposition	20	20	20	20	20	20	20	20	20	20
Fertiliser N	158	158	180	180	37	37	131	131	178	178
Tree leaf litter N	0	0	0	0	0	0	0	0	0	0
Above-ground crop N:	249 ± 18	213 ± 18	67 ± 2	67 ± 12	0	0	124 ± 3	149 ± 8	80 ± 3	89 ± 6
Grain or tuber	0	0	61 ± 2	57 ± 12	0	0	124 ± 3	149 ± 8	70 ± 3	79 ± 6
Biomass	249 ± 18	213 ± 18	6 ± 1	10 ± 2	0	0	-	-	10	10
Total N leaching:	0.2 ± 0	0.4 ± 0.4	45 ± 20	41 ± 6	2 ± 0.4	0.3 ± 0.2	0.5± 0.4	0.1 ± 0.1	2 ± 1	0.7 ± 0.6
NO_3^-	0.2 ± 0	0.4 ± 0.4	42 ± 20	36 ± 6	0.6± 0.2	0	0.5± 0.4	0.1 ± 0.1	2 ± 1	0.6 ± 0.6
NO_4^+	0	0	0.5± 0.1	0.5 ± 0.1	0.1 ± 0	0	0	0	0	0
DON	0	0	2 ± 0.4	4 ± 0.4	0.7± 0.3	0.3 ± 0.2	0	0	0.1± 0	0.1 ± 0.1
Fertiliser P	54	54	30	30	3	3	49	49	25	25
Tree leaf litter P	0	0	0	0	0	0	0	0	0	0
P leaching	0	0	0	5 ± 5	0	0	0	0	0	0
Fertiliser K	62	62	131	131	22	22	136	136	65	65
Tree leaf litter K	0	0	0	0	0	0	0	0	0	0
K leaching	0.2 ± 0	0.1 ± 0.1	19 ± 4	15 ± 3	5 ± 2	0.6 ± 0.4	0.5± 0.4	0.1 ± 0.1	2 ± 1	0.2 ± 0.2
Tree leaf litter C	0	0	0	0	0	0	0	0	2 ± 1	0
Above-ground crop biomass C	9559 ± 656	6785 ± 688	2824 ± 200	2810 ± 303	0	0	4170± 30	5230 ± 160	3975 ± 204	4258 ± 133
DOC leaching	0.1 ± 0.1	0.3 ± 0.3	35 ± 8	59 ± 12	16 ± 6	6 ± 4	0.4± 0.3	0.1 ± 0.1	2 ± 1	1 ± 1

Soil type (site)	Loam Phaeozem (Dornburg)							
Crop rotation (date)	Spring barley 03/2019-07/2019		Fallow 08/2019-02/2020		Winter wheat 10/2020-08/2021		Winter barley 10/2021-07/2022	
Management	AFcrop	OC	AFcrop	OC	AFcrop	OC	AFcrop	OC
N deposition	11	11	11	11	11	11	11	11
Fertiliser N	36	36	0	0	120	120	152	152

Tree leaf litter N	2 ± 7	0	0	0	3 ± 4	0	7 ± 3	0
Above-ground crop N:	109 ± 5	132 ± 8	0	0	167 ± 5	143 ± 20	104 ± 2	108 ± 12
Grain or tuber	79 ± 2	100± 6	0	0	161± 5	137± 20	97± 2	102 ± 12
Biomass	30 ± 5	32 ± 6	0	0	6 ± 1	6 ± 1	7	6
Total N leaching:	2 ± 2	1 ± 1	1 ± 0.1	0.1 ± 0	11 ± 2	5 ± 2	2 ± 1	3 ± 1
NO_3^-	2 ± 2	1 ± 1	1 ± 0.1	0.1 ± 0	10 ± 2	4 ± 2	2 ± 0.7	3 ± 2
NO_4^+	0	0	0	0	0.2± 0.1	0.1 ± 0	0.1 ± 0	0.2 ± 0.1
DON	0.1± 0.1	0	0.1 ± 0	0	0.7± 0.2	0.4 ± 0.3	0.4± 0.2	0.3 ± 0.1
Fertiliser P	22	22	0	0	0	0	0	0
Tree leaf litter P	0.4± 0.1	0	0	0	0.3± 0.1	0	0.3± 0.1	0
P leaching	0	0	0	0	0	0	0	0
Fertiliser K	31	31	0	0	0	0	0	0
Tree leaf litter K	2 ± 1	0	0	0	1± 0.2	0	1 ± 0.3	0
K leaching	0	0	0.1 ± 0	0	0.4± 0.2	0.3 ± 0.2	0.3± 0.1	0.4 ± 0.2
Tree leaf litter C	102 ± 35	0	0	0	96 ± 13	0	44 ± 17	0
Above-ground crop biomass C	3919 ± 168	4648 ± 253	0	0	6034 ± 237	5704 ± 595	3720 ± 120	3605 ± 296
DOC leaching	2 ± 2	0.2 ± 0.1	3 ± 1	0	23 ± 6	8 ± 6	44 ± 23	23 ± 9

Soil type (site)	Clay Cambisol (Wendhausen)					
Crop rotation (date)	Silage corn 04/2019-10/2019		Fallow 11/2019-03/2020		Silage corn 04/2020-09/2020	
Management	AFcrop	OC	AFcrop	OC	AFcrop	OC
N deposition	10	10	10	10	10	10
Fertiliser N	101	101	28	28	120	120
Tree leaf litter N	1 ± 2	0	0	0	3 ± 3	0
Above-ground crop N:	124 ± 14	168 ± 6	0	0	138 ± 4	193 ± 13
Grain or tuber	0	0	0	0	0	0
Biomass	124 ± 14	168 ± 6	0	0	138 ± 4	193 ± 13
Total N leaching:	3 ± 2	3 ± 3	9 ± 2	5 ± 5	7 ± 4	4 ± 4
NO_3^-	3 ± 2	3 ± 3	9 ± 2	5 ± 5	7 ± 4	4 ± 4
NO_4^+	0	0	0.1 ± 0	0	0	0
DON	0.1± 0.1	0.1 ± 0.1	0.2± 0.1	0.1 ± 0.1	0.3 ± 0.2	0.1 ± 0.1
Fertiliser P	0	0	33	33	0	0
Tree leaf litter P	0.2± 0.0	0	0	0	1 ± 0.1	0
P leaching	0	0	0	0	0	0
Fertiliser K	0	0	0	0	0	0
Tree leaf litter K	1 ± 0.1	0	0	0	3 ± 0.3	0
K leaching	0.1 ± 0	0.3 ± 0.1	0.1± 0.1	0.1 ± 0.1	0.1 ± 0.1	0
Tree leaf litter C	34 ± 5	0	0	0	145 ± 13	0
Above-ground crop biomass C	4620± 590	6610± 150	0	0	6180± 150	8040 ± 460
DOC leaching	3 ± 3	0	6 ± 2	7 ± 7	7.± 4	2 ± 2

Table 4: Regression models of mean leaching fluxes as a function of non-collinear controlling factors, presented separately for the alley-cropping agroforestry tree row (AFtree), crop row (AFcrop), and open cropland (OC). Leaching fluxes are expressed in kg N, C or K ha^{-1} per crop rotation or year (for AFtree); sand in percent; precipitation in mm per crop rotation; n = number of crop rotations or years (for AFtree) across three soil types (sites), each an average of 4 plots.

Management	Regression equations	*P* values	R^2	n
AFtree	NO_3^- leaching = 0.003 × (sand × precipitation) + 3.2	0.01	0.39	12
	DON leaching = 0.07 × sand + 0.03 × precipitation + 0.00003 × (sand × precipitation) – 6.7	< 0.01	0.86	12
	K leaching = 0.1 × sand + 0.03 × precipitation – 10.4	0.04	0.40	12
	DOC leaching = 0.001 × (sand × precipitation) + 1.1	0.01	0.61	12
AFcrop	DON leaching = 0.01 × precipitation – 3.3	< 0.01	0.57	12
	K leaching = 0.03 × precipitation − 6.4	< 0.01	0.64	12
OC	DON leaching = 0.01 × precipitation – 2.6	0.03	0.57	12
	K leaching = 0.03 × precipitation − 6.4	0.05	0.26	12

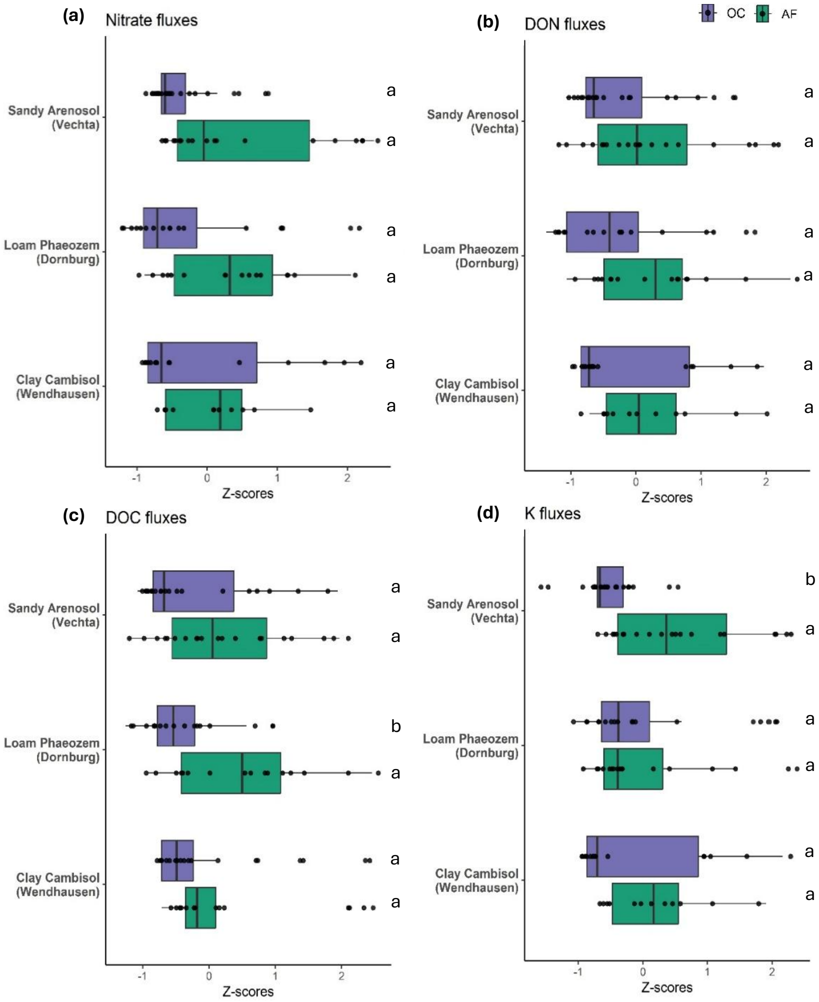

Figure 3: Boxplots of z-standardised leaching fluxes of nitrate (NO_3^-), dissolved organic nitrogen (DON), dissolved organic carbon (DOC), and potassium (K) in alley-cropping agroforestry (AF, green) and open cropland (OC, purple) in the three soil types (sites): sandy Arenosol (Vechta), loam Phaeozem (Dornburg), and clay Cambisol (Wendhausen). AF values are area-weighted average between the tree row and the sampling distances within the AF crop row. Each box represents the interquartile range (IQR) with the median shown as a thick vertical line; whiskers extend to 1.5 × IQR. Z-scores were calculated for each crop rotation as Z = (replicate plot value − overall mean of AF and OC) ÷ standard deviation. Data are presented across all crop rotation periods for each soil type (site): sandy Arenosol (Vechta; n = 4 plots × 5 rotations = 20), loam Phaeozem (Dornburg; n = 4 plots × 4 rotations = 16), and clay Cambisol (Wendhausen; n = 4 plots × 3 rotations = 12). Different letters denote significant differences between systems within a soil type (statistical details in Table S4).

4.2 Leaching dynamics in agroforestry crop rows

Leaching fluxes in AFcrop were influenced by fertilisation timing, synchronisation of fertilisation rate with crop nutrient demand (i.e. NUpE), and precipitation-driven drainage fluxes rather than simply soil texture. On the sandy Arenosol soil, the highest NO_3^- and K leaching fluxes in AFcrop occurred during the winter rye period of 2019–2020, when large amounts of liquid manure and urea were applied (180 kg N ha^{-1} and 131 kg K ha^{-1}; Table 1). This N fertilisation rate exceeded the 100 kg N ha^{-1} commonly applied to winter rye in long-term experiments (Schwarz et al., 2012b). Despite the higher N input in our present study, rye yields (5.4–6.1 Mg ha^{-1}; Choe et al., 2025) were substantially lower than the 8.5 Mg ha^{-1} reported by Schwarz et al. (2012b). The low NUpE of winter rye (0.37; Table 3) signified a mismatch between N fertilisation rate and crop N demand, which likely increased residual N in the soil that was susceptible to leaching. High fertilisation in early spring 2020 coincided with elevated precipitation (570 mm; Table S1) and high drainage fluxes (Fig. 1a), creating conditions conducive to nutrient leaching before effective crop uptake. In contrast, the winter rye period of 2021–2022 on the same sandy Arenosol soil showed 89–95 % lower NO_3^- and K leaching fluxes than the previous two years despite similar manure application (178 kg N and 65 kg K ha^{-1}; Table 1). Lower rainfall (327 mm; Table S1), reduced drainage in early spring 2022, and a higher NUpE (0.45; Table 3) likely explained these reduced leaching fluxes. These results highlight that, in sandy soils typical of livestock-dominated regions in northern Germany (Jacobs et al., 2018), manure application in early spring should be avoided when crop uptake and microbial N immobilisation are still limited (Corre et al., 2002). Synchronising N input with crop demand and seasonal water fluxes are critical to minimize leaching risks.

In the loam Phaeozem soil, the higher NO_3^- leaching in AFcrop at 7 m and 24 m than the OC (Fig. 2e) was mainly contributed by the winter wheat (2020–2021) and winter barley (2021–2022) periods (Table S3). For winter wheat, the 120 kg N ha^{-1} applied in spring 2021 was followed by high rainfall from May to August (50–170 mm month^{-1}), resulting in substantial drainage fluxes (Fig. 1b). For winter barley, the 152 kg N ha^{-1} applied in spring 2022 exceeded the crop N demand (104 kg biomass N ha^{-1}; Table 3). This high N fertilisation rate, combined with elevated drainage in early spring (Fig. 1b) and additional tree leaflitter-N input from 7–8-year-old trees into the AFcrop (3-7 kg N ha^{-1} yr^{-1}; Table 3), likely contributed to the higher NO_3^- leaching in AFcrop compared to OC. On the contrary, the reduced NO_3^- leaching in AFcrop at 1 m (Table S3) suggests the effect of AFtree roots on nutrient uptake, whereby tree roots were higher at 1 m than at farther distances from AFtree (Schmidt et al. 2021). Our results suggest that established AFtree alone does not necessarily reduce NO_3^- leaching in adjacent crop rows (> 7 m from AFtree) when fertilisation rates remain high and hydrological conditions are conducive to leaching.

Similarly, in the loam Phaeozem soil, higher DOC leaching in AFcrop at 1 m and 7 m than in OC (Fig. 2g) was contributed by the high DOC fluxes at these sampling distances during the winter wheat (2020–2021) and winter barley (2021–2022) periods (Table S3). Both these crops had high biomass-C contents (Table S5), added by tree leaflitter-C input from 7–8-year-old AFtree (44–96 kg leaflitter-C ha^{-1}; Table 3). These high crop biomass and tree leaflitter may have stimulated microbial activity upon residue incorporation by ploughing and contributed to DOC as a by-product of decomposition. This was consistent with other studies where DOC leaching increases following organic residue addition under tillage and high rainfall (Jiang et al., 2022; Blanchy et al., 2023). The increase in DOC leaching in the AFcrop may also have implications for microbially mediated NO_3^- removal, as available C (e.g., DOC) has been shown to stimulate denitrification of NO_3^- to N_2 at the same site (Lou et al., 2022). To further understand whether DOC in AFtree and AFcrop will enhance soil C storage at deeper depths, litter decomposition and DOC stabilisation or adsorption at depths are needed in agroforestry system (Schulte-Uebbing et al., 2022). Overall, tree leaf litter and crop residue management, analogous to N fertilisation management, are essential to increase C storage in agroforestry systems.

4.3 Safety-net effect of agroforestry tree roots

The tree-crop interaction zone is strongest at 1 m from the AFtree as evidenced by higher tree root biomass and leaf litter inputs at 1 m than at 7 m and 24 m AFcrop (Schmidt et al., 2021). This was also clearly demonstrated by our findings in the loam Phaeozem soil with 5–8-year-old AFtree in the second rotation, showing two to 10 times lower NO_3^- leaching at 1 m than at 7 m and 24 m AFcrop (Table S3), and higher DOC leaching at 1 m and 7 m than at 24 m AFcrop (Fig. 2g). Reductions in crop yield and biomass-N were also largest at 1 m AFcrop (Table S5), although these reductions did not lead to a decrease in overall (area-weighted) yield of AFcrop compared to OC, particularly for winter crops (Choe, 2026). These findings suggest a win–win situation in mature AF systems with AFtree aged ≥ 5 years, particularly when planted with

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winter crops, whereby yields remain comparable to OC while NO_3^- leaching in the tree-crop interaction zone is substantially reduced. Moreover, tree root biomass at 1 m AFcrop was approximately twice as high at the mature AF in the loam Phaeozem soil compared to the newly established AF in the sandy Arenosol soil (Schmidt et al., 2021). Extensive vertical root systems were also observed in other AF studies with poplar roots reaching deep soil layers within a few years (Allen et al., 2004; Mulia and Dupraz, 2006; Douglas et al., 2016; O'Connor et al., 2024), acting as a biological interceptor for the mineral N left unutilised by the crop (Gikas et al., 2016). Interception by tree roots can be also observed in the N content of wood biomass, averaging 58 kg N ha^{-1} yr^{-1} in 2–4-year-old AFtree during the first rotation on the sandy Arenosol soil, and 83 kg N ha^{-1} yr^{-1} in 5–9-year-old AFtree during the second rotation on the loam Phaeozem soil (Choe, 2026). This suggests higher nutrient absorption by tree roots as tree age increased, referred to as "safety–net" effect of AFtree (Bergeron et al., 2011). The safety–net effect of trees, however, was limited up to ≤ 7 m AFcrop, as discussed above. While the safety-net effect of mature trees reduced leaching of excess nutrients resulting from reduced crop uptake near the AFtree (Table S5), this effect was not enough to reduce leaching in the overall AFcrop below the levels in the OC (Table 3). These results reinforced the importance of fertiliser input synchronisation with the crop demand in AFcrop as the excessive fertilisation can override the tree root interception of nutrients at farther distance from the AFtree.

4.4 Leaching dynamics between agroforestry and open cropland across agroforestry maturity

At the system level, AF did not pose an advantage in nutrient leaching fluxes, as indicators of water quality, compared to OC in all sites (Fig. 3). The three exception cases (Table S4) of higher K and NO_3^- leaching in AF than in OC in the sandy Arenosol soil was attributed to the large liquid manure application combined with soil disturbance from the newly established AFtree and insufficient uptake by young tree roots; and the higher DOC leaching fluxes in AF than in OC in the loam Phaeozem soil was due increased tree leaflitter-C input from 7–8-year-old AFtree (discussed above). The generally comparable leaching fluxes between area-weighted AF and OC (Fig. 3) can be partly explained by the AF layout. In our study sites, the AFtree occupied only 20 % of the area and its effects on intercepting nutrients more than crop demand extended only to ≤ 7 m in AFcrop (discussed above). The greater area of AFcrop suggests that AFcrop management dominated the system-level leaching fluxes. Furthermore, precipitation was identified as the primary driver of DON and K leaching fluxes in both AFcrop and OC (Table 4), consistent with findings in other agricultural systems (van Kessel et al., 2009; Liang et al., 2021). This pattern persisted in AF despite the presence of trees, as nutrient transport in the AFcrop was governed by other factors, such as precipitation-induced drainage flux and the mismatch of fertilisation rates and crop demands. Overall, these findings suggest that to harness the full benefit of AFtree on its function on improving water quality regulation, effective management in AFcrop should be adopted, particularly in reducing fertiliser inputs or synchronising the fertilisation rates with the crop demand combined with residue management (e.g., cover crop termination timing; Nasser et al., 2025) to improve C storage in the soil.

5 Conclusions

Overall, AF did not reduce DOC and nutrient leaching, rejecting our first hypothesis. AFtree and AFcrop exhibited higher NO_3^- and K leaching fluxes than OC in the sandy Arenosol soil during the first two years following AF establishment, attributed to the large liquid manure application combined with soil disturbance from tree establishment and the young age of tree roots. Leaching can be mitigated by growing low nutrient demand crops to warrant low fertilisation rate in the adjacent AFcrop and consequently reduce lateral transfer into the young AFtree. There were also higher DOC leaching fluxes in mature AF system than in OC in the loam Phaeozem, resulted from high tree leaflitter input. This highlights the need for organic matter residue management to minimise DOC leaching or enhanced soil C storage. Nonetheless, mature AF in the loam Phaeozem and clay Cambisol soils, 12–16 years since establishment with 5–8-year-old AFtree in the second rotation, clearly demonstrated two to 10 times lower NO_3^- leaching at 1 m than at 7 m and 24 m in AFcrop. However, the safety-net effect of trees was limited, extending only to ≤ 7 m in AFcrop. This study showed that agroforestry management alone did not necessarily reduce nutrient and organic solute leaching in adjacent AFcrop, as mismatches between fertiliser input and crop nutrient demand under high drainage fluxes drove leaching fluxes in both AFcrop and OC, partly supporting our second hypothesis. Thus, to mitigate leaching across varying soil textures and AF maturity stages, targeted fertiliser management is essential: (1) fertiliser applications should be minimised especially during the first to second year of AF establishment; and (2) fertilisation before high precipitation periods should be avoided, and application rates should be synchronised with crop demand. Ultimately, successful leaching mitigation in AF systems depends on fertilisation management tailored to the specific characteristics of the site, considering soil texture and AF maturity.

Data availability

Data can be accessed at https://doi.org/10.20387/BONARES-BKJE-VB72 (crop, wood, and leaf biomass production, carbon and nitrogen contents in wood and leaf litter from 2018–2023 in Vechta and Dornburg); https://doi.org/10.20387/BONARES-JD29-V977 (Nutrient leaching fluxes in alley-cropping agroforestry and open cropland (2019-2022))

Author contribution

SC: field investigation, data analysis, writing of original draft, visualisation. DN: field investigation, preliminary data analysis. FMR: formal analysis (water modelling). RM: field investigation, writing – review and editing. EV: conceptualisation, methodology, project administration, writing – review and editing, funding acquisition. MDC: conceptualisation, methodology, data interpretation, writing and editing, supervision.

Competing interests

The authors declare that they have no conflict of interest.

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