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The Influence of Hedgerow Planting on the Hydrological Functioning of Two Agricultural Soil Reference Groups

Sofia Biffi[1,2] | Pippa J. Chapman[1] | Richard P. Grayson[1] | Guy Ziv[1]

[1]School of Geography, University of Leeds, Leeds, UK | [2]Agroecology Department, Aarhus University, Tjele, Denmark

Correspondence: Sofia Biffi (fbssbi@leeds.ac.uk)

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ABSTRACT

Woody features can regulate the hydraulic properties of a landscape by influencing water flow paths during rainfall events and reducing runoff, and hedgerow planting is often included in modelling studies as a natural flood management solution. However, very little empirical evidence exists on the effect of hedgerows on soil hydrological properties, particularly when considering different soil groups. This study quantifies the soil physical and hydrological properties that may affect the flood risk mitigation potential of hedges, such as bulk density, porosity, saturated hydraulic conductivity, proportion of flow through different soil pore classes, and water-stable aggregates. We investigated 32 hedges of different age classes (new, 10 year old and old) in the River Eden catchment in north-west England, comparing them to adjacent predominantly grassland fields. We assessed how soil properties varied under hedges on two widespread reference soil groups and examined the orientation of hedges in respect to slope across the entire Eden catchment area. The soil group affected hydrological properties, but, overall, soil under hedges had a larger proportion of smaller soil pores and a better soil structure, with increased soil organic matter and larger soil aggregates, increased soil porosity and improved infiltration rates compared to grassland soils. Soil porosity under hedges was ~17% greater than in grasslands in both soil groups but remained significant at 0–30 cm depth on cambisols and at 0–50 cm only on stagnosols. K_{sat} under hedges was 52 times greater than in adjacent grass fields on cambisols and 45 times on stagnosols, and changes in K_{sat} under hedges on stagnosols occurred over a longer timeframe. Our results show that, in the catchment, hedge orientation of existing hedges is not associated with slope. Our results show that hedge planting has the potential to contribute to flood risk alleviation, but we found that the magnitude is larger and quicker on well-draining soils than on poorly draining soils. These results will aid future natural flood mitigation modelling.

1 | Introduction

The management of agricultural landscapes and their resulting spatial configuration can profoundly affect hydrological dynamics, positioning them as key components in flood risk mitigation planning. Agricultural intensification practices, such as tillage, reduced vegetation cover, increased machinery traffic and high livestock densities have led to soil compaction that can affect hydrological processes and increase run-off (O'Connell et al. 2007). Natural flood management (NFM) in agriculture involves working with natural processes to mitigate flood risk by restoring or enhancing natural features to use them as nature-based solutions (NBS) for the delivery of multiple co-benefits (Sonneveld et al. 2018; Castellari et al. 2021). Thus, practices such as floodplains restoration, wetlands rewetting and the targeted planting of woody species (Lane 2017) have been encouraged across Europe (e.g., Blackwell et al. 2005; Priest et al. 2016; Asselman et al. 2022; DEFRA 2025). Woody features can regulate the hydraulic properties of a landscape, influencing water flows during rainfall events and reducing downstream siltation by reducing erosion (Tyree and Ewers 1991; Marc and Robinson 2007). However, their effectiveness in reducing runoff at the landscape scale, which often relies on modelling studies, is still debated (Carrick et al. 2019; Buechel et al. 2022). Moreover, assessments of the impact of woody vegetation on hydraulic properties of soil has been primarily focused on the role of different types of woodland cover in the landscape and riparian buffers adjacent to river courses (Murphy et al. 2021; Cooper et al. 2021), while little is known about the hydrological properties of soils under hedgerows.

Hedgerows are lines of managed trees and shrubs typical of agricultural landscapes around the world (Montgomery et al. 2020). Hedgerows planting has been linked to the hydrological functioning improvement of agricultural soils, but the hydrological properties of soils under hedgerows are understudied. The conservation and planting of hedgerows is encouraged throughout Western Europe, as they can provide multiple ecosystem services to farmed landscapes, such as supporting faunal and floral biodiversity (Litza et al. 2022; Staley et al. 2023; Biffi et al. 2024a), sequester carbon in their biomass and soil (Biffi et al. 2023, 2025; Black et al. 2023; Drexler and Don 2024), and affect nutrient cycling and hydrology (Holden et al. 2019). The spatial distribution of woody features has a strong effect on soil hydraulic properties and, consequently, in regulating hydrological processes at the watershed scale (Cooper et al. 2021). Our understanding of hedges' impact on hydrological processes in agricultural landscapes is poor and lacking empirical quantification (Ghazavi et al. 2008; Wallace et al. 2021; Kingsbury-Smith et al. 2023), including their predominant orientation along slopes in agricultural landscapes, which can affect their hydrological functioning (Walter et al. 2003; Judson et al. 2025). Despite this, the removal of hedgerows as part of agricultural intensification following field consolidation (Barr and Gillespie 2000) has been anecdotally linked to increased flood risk due to reduction in landscape evapotranspiration and loss of physical barriers perpendicular to slopes to slow surface runoff and trap sediment (O'Connell et al. 2007; Marshall et al. 2014; Wolton et al. 2014). Thus, hedgerow planting interventions have been included as NBS for flood mitigation interventions to attenuate flow and increase water storage during high rainfall and encouraged in national flood management schemes (Wheeler 2016; Dadson et al. 2017; Cooper et al. 2021; Lashford et al. 2022; UK Environment Agency 2025) and they are now commonly included as an intervention in NFM modelling scenario studies (Overhoff 2024; Guillaume et al. 2025).

Hedgerows can affect several physical, chemical and biological properties of the soil that may have a positive effect on soils' hydrological functioning. Hedgerows increase soil organic carbon stocks (Biffi et al. 2022, 2025; Drexler and Don 2024) by increasing light particulate organic matter (POM) (Viaud and Kunnemann 2021; Biffi et al. 2025), the soil organic matter (SOM) fraction that consists of partially decomposed plant residues and that is most susceptible to land use change. This increase is likely due to changes in litter accumulation and fine root and hyphal turnover (Godbold et al. 2006; Yan et al. 2018). As increased POM content is linked to improvements in the structural stability and pore structure of agricultural soils (Buchmann and Schaumann 2018; Ding et al. 2025), soil aggregates and pore size distribution are likely to improve as a result of hedgerow planting on agricultural soils (Guest et al. 2022; Shi et al. 2023). Moreover, hedges, and particularly managed hedges, are shrub-like vegetation characterised by a high below-ground to aboveground biomass ratio (Axe et al. 2017; Drexler et al. 2024). Their enhanced root systems may facilitate vertical water flow through root channels, increasing hydraulic conductivity (the ease with which water moves through pore spaces) under hedges compared to agricultural fields (Webb et al. 2022; Jarecke et al. 2025). Moreover, the soil type on which hedgerows are planted is likely to affect the hydraulic properties of the soil under them, as differences in soil texture and drainage characteristics, as well as soil organic carbon (SOC) content, can influence the water holding and infiltration capacity of agricultural landscapes (Van De Genachte et al. 1996; Thompson et al. 2010; Vopravil et al. 2020; Basset et al. 2023).

Few empirical studies have been conducted on the hydrological properties of hedgerows. Soil under hedges has been shown to have increased water absorption and storage capacity, and studies have shown that hedges intercept rainfall and increase evapotranspiration relative to adjacent agricultural fields, increasing water storage capacity in an area twice as wide as the hedge's height (Herbst et al. 2006; Ghazavi et al. 2008, 2011; Thomas et al. 2012; Holden et al. 2019). Hawthorn (*Crataegus monogyna* L.), the most dominant hedgerow species in the UK, has been associated with particularly high rates of evotranspiration compared to other hedgerow species (Herbst et al. 2007). Benhamou et al. (2013) showed that a catchment with 1.5% hedge coverage of total agricultural area had a reduced water flow of 4.5% compared to a catchment without hedges. Soil under hedgerows has been shown to have a greater proportion of soil macropores at 0–50 cm depth compared to adjacent grassland or arable fields (Holden et al. 2019), and to have 22–27 times greater saturated hydraulic permeability in two replicate pair-plots of hedges and pastures (Wallace et al. 2021). Another small study on one hedgerow in northern England (Coates 2018) showed that hedge structure altered rainfall spatial distribution due to canopy interception in the immediate area and increased saturated hydraulic conductivity.

Although the few studies that exist suggest that planting hedgerows has the potential to improve soil structure and thus infiltration rates in agricultural landscapes, there is a lack of knowledge about that rate at which changes in these soil properties occur. Therefore, to address this knowledge gap, this paper uses a space-for-time substitution approach to quantify the soil physical and hydrological properties that affect runoff and therefore flood risk in the landscape (bulk density, porosity, hydraulic conductivity, proportion of flow through different pore classes and water-stable aggregates) under hedges of known age categories and in adjacent predominantly grassland fields. To address the potential role that soil type may have on this effect, we sampled two Reference Soil Groups (WRB 2015), cambisols and stagnosols, which are typical of landscapes dominated by dairy and beef farming in England. Cambisols are the most widespread reference soil group in Europe (27% of total land area), and stagnosols are related to luvisols, which are the second most widespread soil group in Europe (15%, Tóth et al. 2008) and they occur across north-west European regions (ISRIC 2025). We assessed the differences in soil properties at 10 cm intervals over the 0–50 cm depth profile between these two soil groups and between hedges and fields on the same soil group. We hypothesised that (i) soil group would affect the difference in soil physical and hydrological properties between hedges and fields and that (ii) hedgerow age would have a positive impact on the soil hydrological properties of hydraulic conductivity, the proportion of flow through each pore class and aggregate size distribution. Finally, we performed a large-scale analysis of the orientation of hedgerows in the Eden catchment, Cumbria, to determine whether hedgerow distribution exhibits preferential orientation patterns along slopes, as this may affect the effectiveness of hedgerows as a NBS for flood risk alleviation at the watershed scale.

2 | Materials and Methods

2.1 | Study Sites and Soil Groups

This study was conducted in the county of Cumbria, Northwest England, in the river Eden catchment, a rural area characterised by dairy and beef farming. The Agricultural Land Class of the area is grade 3 ('good to moderate quality agricultural land'; Natural England 2010) and the Koppen climate classification of the region is temperate oceanic (Beck et al. 2018), with an average annual temperature across the five farms of 8.8°C, average annual rainfall of 1092 mm and altitude of 135 m asl (see Biffi et al. 2022, 2023 for more information). The agricultural area in the catchment is dominated by improved (66%) and seminatural (21%) grassland with some arable production (13%, Morton et al. 2024). The study took place on five farms, which were characterised by two main soil reference groups according to the National Soil Map of England and Wales (Cranfield University 2018): (1) cambisols, which are freely draining (2) stagnosols, which are slowly permeable, seasonally wet soils (WRB 2015). These soil groups occur extensively across England, 15.5% and 19.9% respectively, with the cambisols suitable for a range of crops and characterised by a long grazing season when under grass production and stagnosols mostly suited for grass production, with some cereal production for livestock feed (Cranfield University 2018). The fields sampled in the study were permanent pastures (83%) or grass leys with the occasional arable crop (19%). They were intensively managed and predominantly classified as MG7 ('*Lolium perenne* L. reseeded grassland'), and most were annually cut at least once for silage. The average slope among fields was 1.7° (range 0.2°–8.6°; Environment Agency 2022).

2.2 | Hedgerows Characteristics

The hedgerows sampled in this study are described in detail in Biffi et al. (2022, 2023). While hedges may top earth banks or stone walls, all hedges in our study were planted directly into soil around the boundaries of fields. Thirty-two hedgerows were selected among five farms and grouped into three age categories: (1) 'new' if they were planted between 2017 and 2020, 8 hedges in total, (2) '10-year-old' if they were planted between 2016 and 2010, 8 hedges in total (3) 'old' if they were planted before 2010, 16 hedges in total (these were mature hedgerows for which the exact year of planting was not known, ranging from decades to potentially hundreds of years old, with 8 hedges being planted in 1983). The number of hedges per soil group is shown in Figure 1. New and 10-year-old hedges were planted following standard hedgerow planting guidance, with a minimum of six plants per meter (Rural Payments Agency and Natural England 2015). Woody species composition of the hedges was typical of England and Cumbria (Barr and Gillespie 2000; Carey et al. 2007; Cumbria Biodiversity Data Centre 2010) and was dominated by hawthorn (70%) and blackthorn (15%). All old hedges were regularly managed by being mechanically trimmed every 1–2 years and laid every 20–30 years. All hedgerows, apart from two old hedges, were planted where according to 18th century mapping hedgerows had been historically present (EDINA 2010).

2.3 | Soil Physical Properties

For a detailed description of the soil sampling approach and laboratory analysis see Biffi et al. (2022). Briefly, in 2021, at each sampling location (i.e., directly under the hedge and 16 m into the adjacent field), a 5 cm diameter ring corer (Eijkelkamp, NL) was used to take intact 100 cm^3 soil cores representing soil layers at 0–10, 10–20, 20–30, 30–40 and 40–50 cm depth for the determination of bulk density. Grab soil samples were also collected

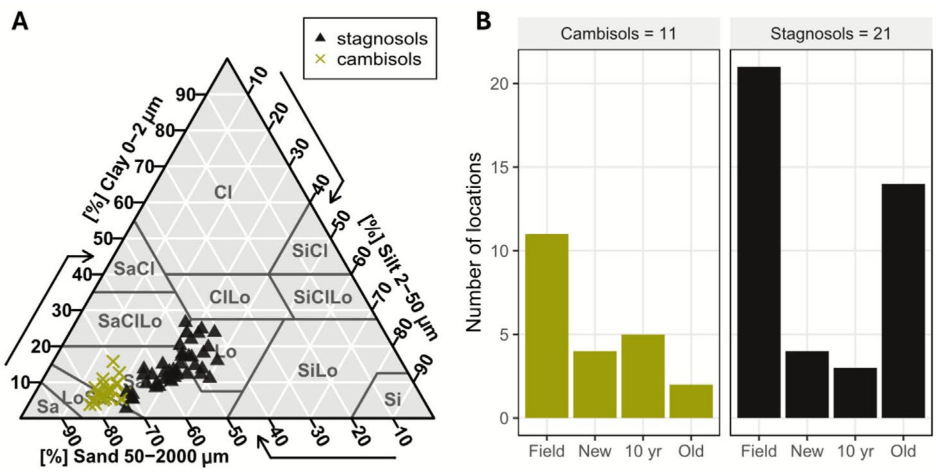

FIGURE 1 | (A) Distribution of soil particle size fractions among the stagnosols (triangles) and cambisols (crosses) sampled in the study on the USDA soil texture triangle, and (B) number of field and hedgerow sampling locations on cambisols and stagnosols. Field and hedges sampling locations were paired in a space-for-time substitution approach. The total number of pairs for each soil group is shown in the facet label.

from each depth interval for the determination of SOM and SOC content. Grab soil samples at 0–10, 10–20 and 30–40 cm depths were taken for the determination of soil pH. Grab samples at 0–10 cm depth were taken for the determination of soil particle size distribution and water-stable aggregates. Bulk density (BD g cm^{-3}) was calculated after drying at 105°C as the difference between the total sample mass and the coarse mass, divided by the sample volume. Particle density (g cm^{-3}) was determined with the water displacement method as the mass of soil fine fraction (< 2 mm) divided by the volume of the soil fine fraction. SOM content (g cm^{-2}) was determined via the loss on ignition method (550°C for 16 h). SOC content (g kg^{-1}) was determined using an Elemental Vario EL cube (Elementar Analysensysteme GmbH, Germany). Soil pH was measured with a pH meter (pH700 benchtop meter, Oakton) in a suspension of air-dried soil (< 2 mm) in deionised water at a 1:2.5 ratio.

For each soil sample, soil porosity (cm cm^{-3}) was calculated as:

$$\text{Porosity} = 1 - \frac{\text{Bulk density}}{\text{Particle density}}$$

Soil particle size was determined using grab soil samples at 0–10 cm depth by adapting the gravimetric method in (Van Reeuwijk 2002). Briefly, 100 mL of deionised water was added to 10 g of air-dried, homogenised soil. A 5% sodium hexametaphosphate (Calgon) solution was added for 16 h to promote the disaggregation of fine mineral particles. The suspension was wet-sieved through a 53 μm mesh to separate the sand fraction (53–2000 μm). The clay fraction (< 2 μm) was determined using the pipette method. The USDA soil texture class of each soil sample was extracted from the soil particle size distribution using the soil texture package in R (Moeys et al. 2024). The sampling sites, which were classified as cambisols or stagnosols according to the National Soil Map of England and Wales (Cranfield University 2018), showed distinctive clusters of soil texture, with cambisols being characterised by higher sand content than stagnosols (Figure 1).

2.4 | Saturated Hydraulic Conductivity (K_{sat})

Intact core samples from 0 to 10, 10–20 and 30–40 cm depth were analysed in the laboratory to obtain saturated hydraulic conductivity (K_{sat}, cm s^{-1}) using a constant-head/falling head laboratory permeameter (Eijkelkamp, NL). K_{sat} was also expressed as mm h^{-1} by multiplying results in cm s^{-1} by 36,000. Due to the log-normal distribution of K_{sat} values, geometric means were calculated for this property instead of arithmetic means. Finally, the relative difference in K_{sat} between each pair of hedges and fields was calculated as :

$$R_{\text{Ksat}} = \frac{K_{\text{sat hedge}}}{K_{\text{sat field}}}$$

2.5 | Unsaturated Hydraulic Conductivity and Flow Through Different Pore Sizes

In summer 2022, tension minidisk infiltrometers (METER Group Inc. USA) placed on a thin sand layer to ensure good contact between the tension disc and soil surface were used to measure infiltration in field conditions and calculate unsaturated hydraulic conductivity (K, cm s^{-1}). Pressure heads equal to −6, −3 and −0.5 cm tension were used to exclude water flow through micropores (0.25–0.5 mm), mesopores (0.5–1 mm), and macropores (> 1 mm), respectively. Three replicate measurements were taken from each location and K measurements were made in ascending tension sequence. To reduce the time required for the sampling, an automated set-up was used whenever possible (Klípa et al. 2015) using a PX26 differential pressure transducer (Omega Engineering Inc. USA) recording pressure every 5 s. Water volume in the automated set up was manually checked and recorded every few minutes. To reduce noise in the automated readings, the 5-second interval readings of each tension level were smoothed using an exponential moving average with a 1-minute window (movavg in package pracma, Borchers and Borchers 2019). The manual readings taken in the automated system were regressed against smoothed pressure readings, stratified by land cover type and tension level, to estimate water volumes from continuous pressure data. Cumulative infiltration (cm) was then calculated from the change in estimated volume over time, normalised by the infiltrometer ring area (radius 2.25 cm), with the initial three time points removed to avoid artefacts from surface disturbance.

Infiltration rates (K, cm s^{-1}) were calculated from manual and automated measurements for each replicate and tension level and used to partition flow into pore size classes following Watson and Luxmoore (1986). Macropore flow was estimated as $K_{0.5}$–K_3, mesopore flow as K_3–K_6 and micropore flow as K_6, with total flow defined as $K_{0.5}$. Values were converted to percentages of total flow to quantify the relative contribution of each pore class. Replicates with percentage totals deviating more than ±10% from 100% were excluded to remove instances of increasing flow values with increasing tension due to measurement error, and the remaining percentage contributions were rescaled to 100%.

2.6 | Water-Stable Aggregate Fractionation

Water-stable aggregates (WSA) were measured from grab samples at 0–10 cm depth following Guest et al. (2022) using a methodology adapted from Elliott (1986) and Loaiza Puerta et al. (2018). Briefly, the fresh soil samples were wet-sieved by hand through a series of sieves (2, 1, 0.25, 0.053 mm) to obtain five WSA size fractions using the mean weight diameter approach (MWD). The fraction size classes were large macroaggregates (> 2 mm), medium macroaggregates (1–2 mm), small macroaggregates (250 μm–1 mm), microaggregates (53–250 μm) and silt and clay (< 53 μm). We computed the WSA percentage for each fraction by dividing the dry mass of that aggregate fraction to the total dry soil mass minus the coarse mass fraction (> 2 mm). MWD was then calculated by summing the products of each fraction's mean sieve diameter (3, 1.5, 0.625, 0.1515, 0.0265 mm) and its proportional weight. Mean total recovery rate was 99.1% ± 1.3%.

2.7 | Large Scale Analysis of Hedgerow Orientation Along Slopes

To assess hedgerow orientation relative to terrain in the Eden catchment, we used the UKCEH Land Cover Plus Hedges dataset

(Broughton et al. 2024) that maps hedges in arable, improved grassland and semi-natural grassland agricultural landscapes. It should be noted that these can include uplands area that were not subject to the Enclosure Act (Williamson 2000) and are thus less likely to have hedgerows to define field margins. Woody linear features ≥1.5 m in height were intersected with a 1 m resolution DTM-derived slope and aspect model (Environment Agency 2022). The angular deviation ($\Delta Angle_{h[0,90]}$, °) between each segment's orientation and the local downslope direction was calculated using the atan2 function (Hijmans et al. 2013) in Google Earth Engine (Gorelick et al. 2017), where 0° indicates alignment with slope and 90° indicates perpendicular orientation. For further details on the calculations, see Data S1. Terrain slope classes (≤5°, 5°–10°, 10°–20°, 20°–30°, >30°) were used to calculate mean $\Delta Angle_{h[0,90]}$ and hedge density (km km^{-2}) by class.

2.8 | Data Analysis

All analyses were conducted in R v4.4.1 (R Core Team 2023). Differences in soil and hydraulic properties in fields and under hedges of different ages and different soil groups were investigated using Student *t*-tests and ANOVA or, when the data distribution did not meet the assumption of normality, non-parametric Mann–Whitney–Wilcoxon tests and Kruskal–Wallis rank tests. Post-hoc tests were conducted with Tukey's Tests or non-parametric Dunn's tests for pairwise multiple comparisons with Benjamini-Hochberg false discovery rate-corrected *p*-values. Differences were considered significant at $\alpha = 0.05$. To investigate the effect of soil group on the relationship between hydraulic conductivity and soil characteristics of porosity, SOC content and sand content under hedges of different ages, we fitted three separate linear models to describe log10-transformed K_{sat} based on sampling depth interval, land use (field/hedge age category) and soil group (cambisols/stagnosols) as categorical variables, and one of the soil characteristics as continuous predictor. A full model with all categorical variables and porosity and clay content as continuous predictors was also run, excluding SOC content due to multicollinearity. Correlations between the different soil characteristics are shown in Data S2. Predictors were scaled for comparability of effect size.

3 | Results

3.1 | Soil Properties of Different Soil Groups

When all hedge and field samples were considered together, soil properties were significantly different between cambisols and stagnosols soil groups (Table 1). Cambisols had higher bulk density ($\chi^2 = 13.9$, $p < 0.001$), while stagnosols had significantly higher porosity ($\chi^2 = 10$, $p < 0.001$), SOM ($\chi^2 = 82.6$, $p < 0.001$) and SOC content ($\chi^2 = 25.8$, $p < 0.001$). The soils sampled ranged in soil texture, with sand content ranging 41.1%–81.3%, silt 13.8%–40.2% and clay 3.8%–26.6% (Figure 1). Soil particle size fractions significantly differed between cambisols and stagnosols, with cambisols containing higher sand ($\chi^2 = 205$, $p < 0.001$), and stagnosols higher in silt ($\chi^2 = 207$, $p < 0.001$) and clay ($\chi^2 = 136$, $p < 0.001$). The two

TABLE 1 | Mean (± SD) of bulk density (BD), particle density (PD), porosity, pH, soil organic matter content, total SOC and mineral particle size classes in soil under hedges and adjacent grassland fields on cambisols and stagnosols at 0–50 cm depth. pH values are averaged from depth intervals of 0–10, 10–20, 30–40.

SRG	Land use	BD ($g\,cm^{-2}$)	PD ($g\,cm^{-3}$)	Porosity ($cm\,cm^{-3}$)	pH	SOM ($g\,kg^{-1}$)	SOC ($g\,kg^{-1}$)	Clay (%)	Silt (%)	Sand (%)
C	All	**1.38±0.25**	**2.43±0.11**	0.43±0.11	5.3±0.4	50.1±30.8	20.4±15.6	7.6±2.9	17.2±2.4	**75.2±3.2**
S	All	1.25±0.28	2.39±0.17	**0.48±0.12**	**5.6±0.7**	**86.6±40.5**	**32.1±23.9**	**14.9±5.2**	**30.7±4.2**	54.4±7.3
C	Field	1.48±0.21	2.44±0.09	0.4±0.08	5.9±0.2	45.5±26	18.3±13.7	7.6±2.6	17.8±2.3	74.6±2.9
	Hedge	**1.28±0.25**	2.41±0.13	**0.47±0.12**	**5±0.6**	54.6±34.6	22.4±17.2	7.5±3.1	16.6±2.2	75.9±3.4
S	Field	1.35±0.25	2.43±0.18	0.44±0.1	6±0.5	75±31.2	25.4±18.2	14.5±5	31.8±4.3	53.7±6.9
	Hedge	**1.14±0.27**	**2.36±0.17**	**0.52±0.11**	**5.2±1**	**98.5±45.4**	**39.1±26.9**	15.3±5.5	29.6±4.8	55.1±7.6

Note: Values in bold indicate significantly higher soil properties between the two soil groups under all land uses, or statistically different soil properties under hedges compared to adjacent fields of the same soil group ($\alpha = 0.5$). Cambisols $n = 22$, stagnosols $n = 42$.

soils also significantly differed in pH, with stagnosols being less acidic than cambisols.

3.2 | Soil Properties of Hedges and Fields on Different Soil Groups

Soil properties significantly differed between hedges and fields for both soil groups at 0–50 cm depth (Table 1, results by sampling depth intervals in Data S3). Bulk density was lower, and porosity was higher in soil under hedges than in adjacent grassland fields for both cambisols (BD: $W = 2111$, $p < 0.001$, porosity: $W = 827$, $p < 0.001$) and stagnosols (BD: $W = 7599$, $p < 0.001$, porosity: $W = 2944$, $p < 0.001$). Across all soil depth intervals, porosity under hedges increased by 17% in cambisols and 18% in stagnosols. However, when separate depth intervals were considered, the difference in porosity between hedge and field soil remained significant at all depth intervals for stagnosols, while for cambisols they were significant to 30 cm depth only (Figure 2). Soil pH was significantly lower in soil under hedges than in fields for both soil groups; however, while this difference was significant at all depths for cambisols, it was only significant at the lowest interval measured (30–40 cm) in stagnosols (Data S3). SOM content and SOC content were significantly higher under hedges on stagnosols, but not on cambisols soils (Table 1). Soil particle size fractions did not differ significantly between hedges and fields on the same soil group.

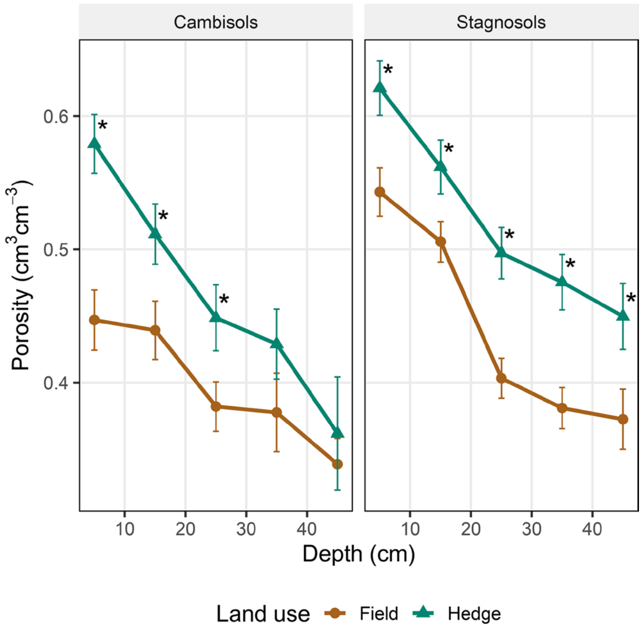

FIGURE 2 | Vertical distribution of soil porosity (mean ± SE) across mid-depth intervals (cm) under hedge and field management across two soil groups (cambisols and stagnosols). Lines connect mean values for each land use type, with point shape indicating land use (circle = Field, triangle = Hedge). Asterisks indicate significantly higher porosity in soil under hedges than in fields within the same depth interval according to Mann–Whitney-Wilcoxon tests (alpha = 0.5). Sample sizes on cambisols: Field ($n = 11$), hedge ($n = 11$); on stagnosols: Field ($n = 21$), hedge ($n = 21$).

3.3 | K_{sat} Under Hedges on Different Soil Groups

Across all depths, K_{sat} varied with soil group and land use (Table 2). Mean K_{sat} was 10 times higher for grass fields on cambisols than stagnosols ($W = 1295$, $p = 0.016$). Overall, mean K_{sat} was 36 times higher for soils under hedges than in adjacent grassland fields (10.8 vs. 0.3 mm h^{-1}, $W = 1891$, $p < 0.001$) and this difference was significant for both cambisols ($W = 175$, $p < 0.001$) and stagnosols ($W = 878$, $p < 0.001$). Total K_{sat} on cambisols was 52 times greater under hedges than in fields (51.6 vs. 1.0 mm h^{-1}), while on stagnosols it was 45 times higher (4.5 vs. 0.1 mm h^{-1}).

The mean difference in infiltration rate between pairs of hedges and fields (R_{Ksat}) showed that soil under hedges on cambisols had a mean additional infiltration rate of 53 ± 2 mm h^{-1} compared to fields, and K_{sat} did not vary significantly among hedges of different ages (Figure 3). Soil under hedges on stagnosols had a mean R_{Ksat} of 29 ± 1 mm h^{-1}. However, K_{sat} under new hedges on stagnosols was not significantly different to that in fields (Figure 3). When this age category was excluded, the R_{Ksat} of soil under hedges of 10 years or older was 61% greater than in fields on stagnosols and 255% greater for cambisols. K_{sat} distribution by depth interval (Data S4) suggested that the 0–10 cm depth

TABLE 2 | Number of replicates, geometric mean (± log-SD) K_{sat} of different soil reference groups (SRG) on soil under hedges and in adjacent grassland fields, with values in brackets indicating back-transformed ±1 SD from the log10-transformed mean (68% CI) and geometric mean (± log-SD) ratio of K_{sat} under hedges compared to adjacent grassland fields (R_{Ksat}).

SRG	Land use	*N*	K_{sat} (mm h^{-1})	R_{Ksat}	R_{Ksat} ≥ 10 year
Cambisols	All	65	7.3 ± 1.6 [0.2, 288.8]		
Stagnosols	All	121	0.7 ± 1.6 [< 0.1, 30.4]		
All	Field	94	0.3 ± 1.5 [< 0.1, 9]		
	Hedge	92	10.8 ± 1.4 [0.4, 265.7]		
Cambisols	Field	32	1.0 ± 1.7 [< 0.1, 49.3]		
	Hedge	33	51.6 ± 0.9 [6.9, 389]	53.3 ± 2.0	189.7 ± 2.0
Stagnosols	Field	62	0.1 ± 1.4 [< 0.1, 3.1]		
	Hedge	59	4.5 ± 1.5 [0.1, 137]	28.8 ± 1.4	46.4 ± 1.4

Note: All values are expressed in mm h^{-1}.

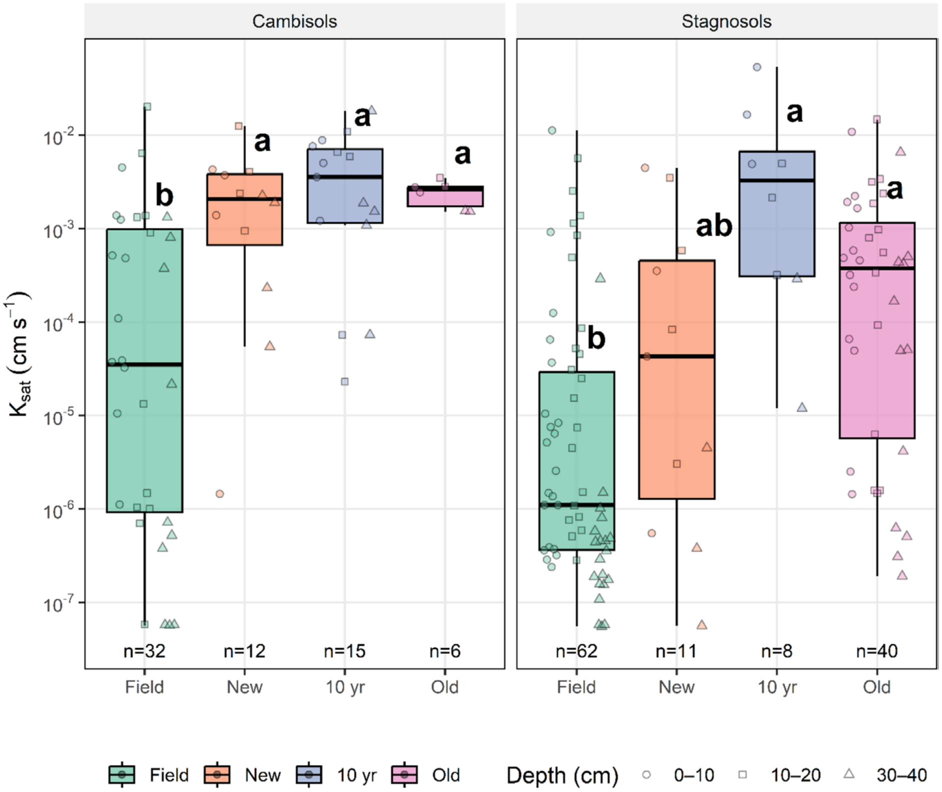

FIGURE 3 | Saturated hydraulic conductivity (K_{sat}) for soil samples at 0–10, 10–20 and 30–40 cm depth under hedges of different ages and adjacent grassland fields on cambisols and stagnosols, as measured on a laboratory permeameter. Box plot shows median and first and third quartiles (the 25th and 75th percentiles). Different letters indicate statistically significant differences according to post hoc Dunn's tests within the same soil group ($p < 0.05$).

layer contributed more significantly to the higher infiltration rates under hedges compared to fields than lower soil depths, particularly on cambisols. However, the limited sample size of K_{sat} stratified by soil group and soil depth reduced the robustness of the analysis.

The linear models of log-transformed K_{sat} and soil characteristics also highlighted the role of soil group and land use on K_{sat}. Hedges showed higher K_{sat} than fields in all models, with larger effect sizes for hedges older than 10 years than new hedges (Data S5). K_{sat} also declined significantly with soil depth interval, although the effect size was small. Soil porosity ($R^2 = 0.44$) and SOC content ($R^2 = 0.47$) were significantly positively associated with K_{sat}, whereas clay content ($R^2 = 0.43$) showed a significant negative association (Figure 4). Soil group showed a significant effect in all models, except when only considering clay content (as the two soil groups had significantly different clay content, Table 1, Figure 1).

3.4 | Flow Though Pore Size Classes Under Hedges on Different Soil Groups

Overall, unsaturated hydraulic conductivity under hedges and in adjacent grassland fields did not vary strongly (Data S6), and only K_6 differed significantly between cambisols (13 ± 14 mm h^{-1}) and stagnosols (7 ± 9 mm h^{-1}, $W = 1828$, $p = 0.021$), whereas $K_{0.5}$ and K_3 did not change significantly between soil groups. When only field samples were considered, the two soils groups did not differ significantly in any of the K tension levels. K_6 for hedges on cambisols was significantly higher (18 ± 16 mm h^{-1}) than for hedges on stagnosols (8 ± 8 mm h^{-1}, $W = 579$, $p = 0.015$).

Overall, the proportion of flow through each pore class (Figure 5) was only significantly different between the two soil groups for micropores (11% ± 9% in cambisols vs. 6% ± 10% in stagnosols, $W = 1878$, $p = 0.009$), whereas it did not vary significantly for macropores and mesopores (mean and SD 76% ± 26% and 17% ± 20%, respectively).

When looking at all hedges and fields together, the proportion of flow through each of the three pore size classes significantly differed between hedges and fields, with hedges lower in macropore flow (65% ± 31% vs. 87% ± 12%), and higher in mesopore (25% ± 24% vs. 8% ± 9%) and micropore flow (9% ± 13% vs. 5% ± 6%) compared to fields. However, when soil reference groups were analysed separately, the proportion of flow through each pore class was significantly different under hedges compared to fields on stagnosols, but not on cambisols. For stagnosols, macropore flow was higher in fields (91% ± 1%) than under hedges (72% ± 4%, $W = 1412$, $p < 0.001$), while mesopore (20% ± 3% vs. 6% ± 1%, $W = 517$, $p < 0.001$) and micropore flow (9% ± 2% vs. 3% ± 1%, $W = 667$, $p = 0.018$) were higher under hedges than in fields. This pattern was reflected throughout the hedge age categories (Figure 5).

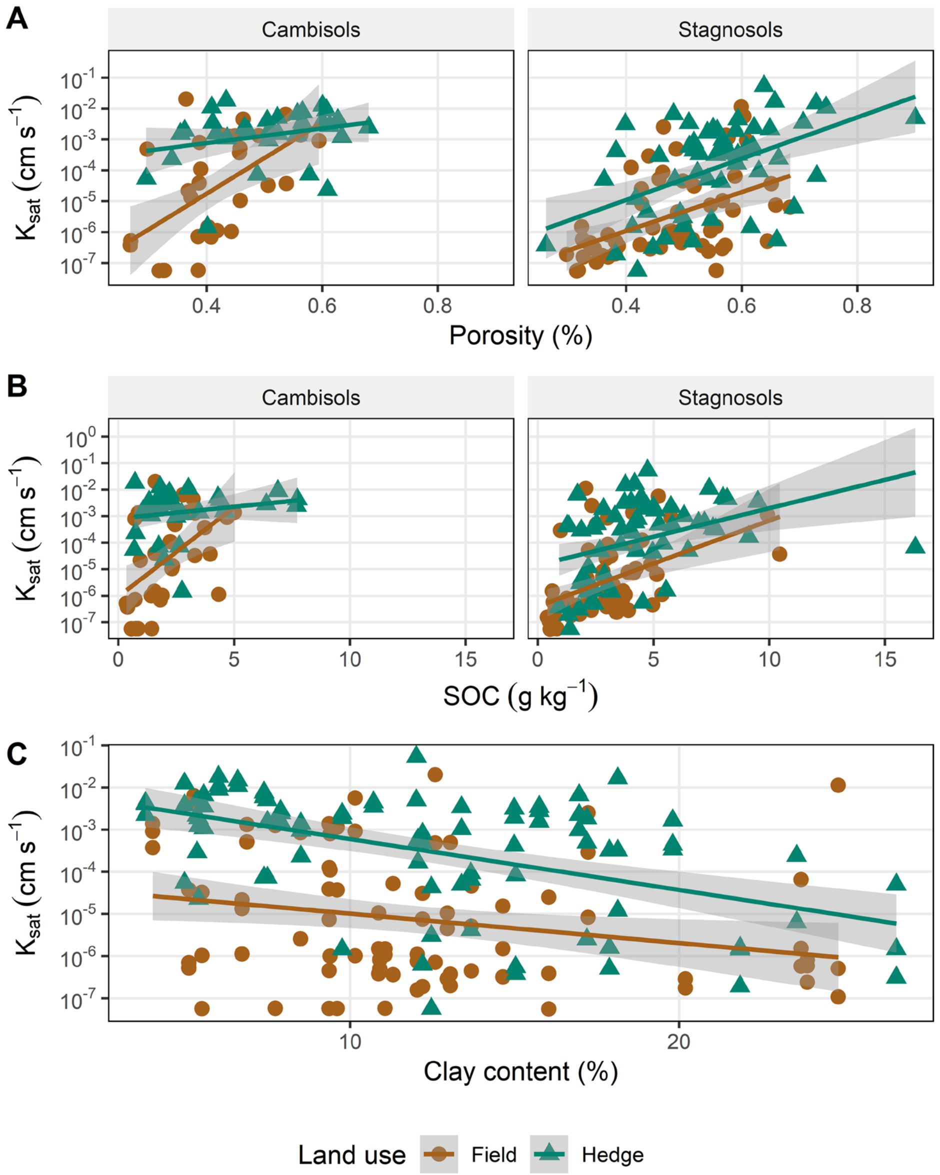

FIGURE 4 | Relationship between saturated hydraulic conductivity (K_{sat}) from soil samples at 0–10, 10–20 and 30–40 cm depth with (A) porosity, (B) SOC content and (C) clay content of soil under hedges and in adjacent grassland fields. Point shape indicating land use (circle = Field, triangle = Hedge). The solid lines with the grey band represent linear regression lines and their 95% confidence intervals.

3.5 | Aggregate Size Classes After Hedgerow Planting

Aggregate size fraction distribution varied between the two soil groups, with stagnosols samples showing a higher proportion of >2 mm aggregates (91% ± 9%) than cambisols (77% ± 20%, $W = 214$, $p < 0.001$). Aside from the clay fraction <53 μm, which did not differ between soil groups, all other aggregate fractions were significantly higher in cambisols than in stagnosols ($p < 0.001$).

To increase the robustness of the analysis on our sample size, hedges of 10 years and older were pooled together to examine the distribution in aggregates between established hedges and fields on different soil groups (Figure 6A).

Hedges on cambisols had a significantly higher proportion of large macroaggregates and a lower proportion of medium and smaller aggregates, while the clay fraction (<53 μm) did not change between hedges and fields. Aggregates >2 mm increased by 14% under hedges, while 1–2 mm aggregates decreased by 27%, 1 mm–250 μm decreased by 63%, and 250–53 μm decreased by 68%. Hedges on stagnosols did not show significant differences in aggregate size distribution compared to fields. However, the large macroaggregate fraction (>2 mm) was close to being significantly higher under hedges than in fields for stagnosols ($W = 113$, $p = 0.056$).

The particle size distribution did not significantly change with hedgerow age; however, Figure 6B visually suggests a progressive increase in the macroaggregate fraction and a decrease in the medium and smaller fractions between fields, newly planted hedges and hedges of 10 years or older.

Figure 7 shows the relationship between changes in aggregate size fractions and corresponding changes in flow contribution

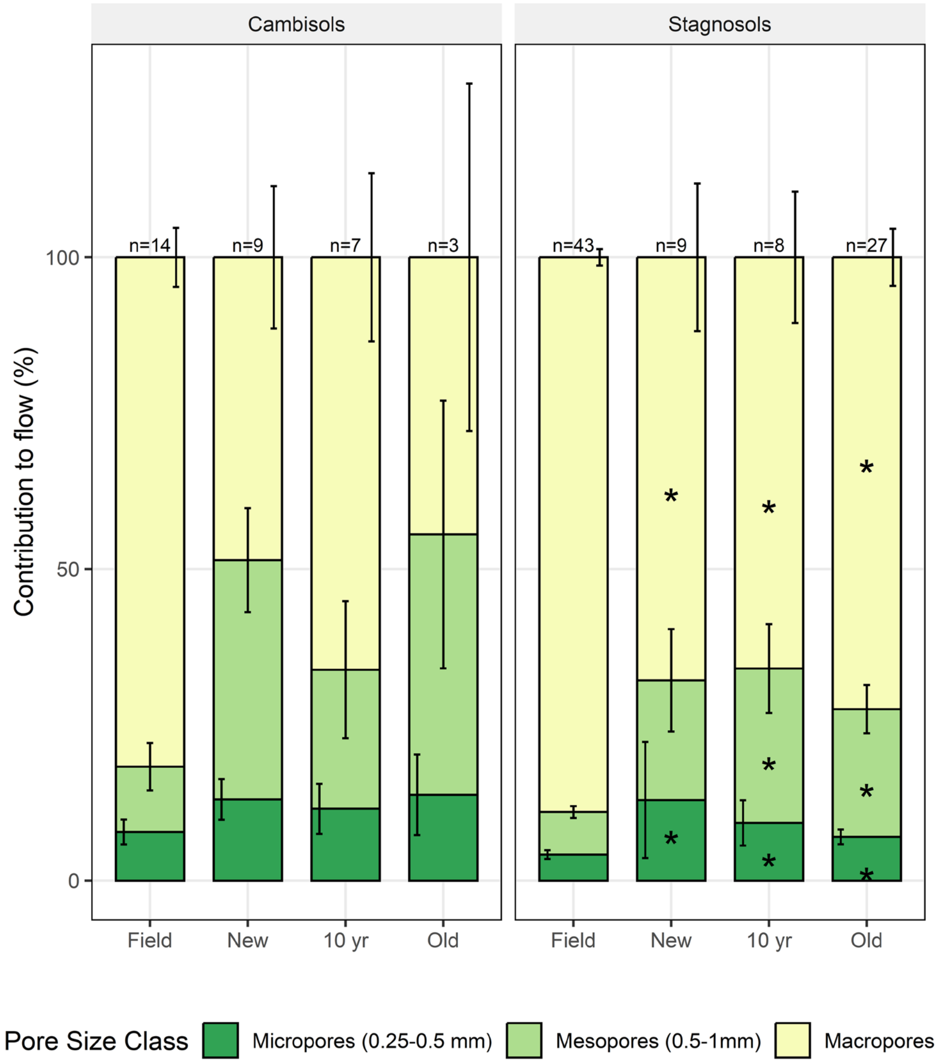

FIGURE 5 | The proportion of flow through each pore class in fields and under hedges of different ages, shown as mean (± SE) proportion of water flow through each pore size class for each soil reference group. The sample size at the top of each bar represents the total number of samples used to calculate the mean, after excluding samples with a total flow outside of the 100% ± 10% range. Asterisks indicate statistically significant differences in flow through a particular pore size class under hedges compared to adjacent grassland fields, according to post hoc Dunn's tests ($\alpha < 0.05$). No significant differences were found among the hedge age classes.

of different pore size classes in the transition from grassland to hedgerows of different ages. The increase in macroaggregates (> 1 mm) and decreased in smaller aggregate fractions under hedgerows was accompanied by a larger flow contribution of meso- and micropores, and a reduction in the flow contribution of macropores, suggesting a functional reorganisation of the pore system under hedges.

3.6 | Orientation of Hedgerows on Cumbrian Slopes

We found a total of 6244 km of hedges around agricultural fields in the Eden catchment, and the average hedge density was 2.9 km km^{-2}. The highest hedge density (4.4 km km^{-2}) was found on slopes of 5°–10° and then the density progressively decreased as the angle of slopes increased and the amount of semi-natural grassland increased (10°–20°: 3.2, 20°–30°: 2.1, 30°+: 1.6 km km^{-2}). The orientation of hedgerow segments compared to slope was consistent among slope classes, with a mean of 46° ± 26°, indicating hedges were not aligned with the slope direction on flat or steep terrain, and were not predominantly oriented parallel or perpendicular to slopes (Data S1).

4 | Discussion

4.1 | Soil Characteristics Between Hedges and Fields on Different Soil Groups

The reference soil group strongly influenced the soil characteristics of bulk density, porosity and soil particle size. We found that cambisols, which were higher in sand content, had higher bulk density and lower soil porosity than stagnosols, which had significantly higher silt and clay content. Soils higher in sand content tend to have higher bulk densities, as they have larger, but fewer pore spaces compared to soils rich in fine silt and clay, which have a larger proportion of small pores (Jones 1983;

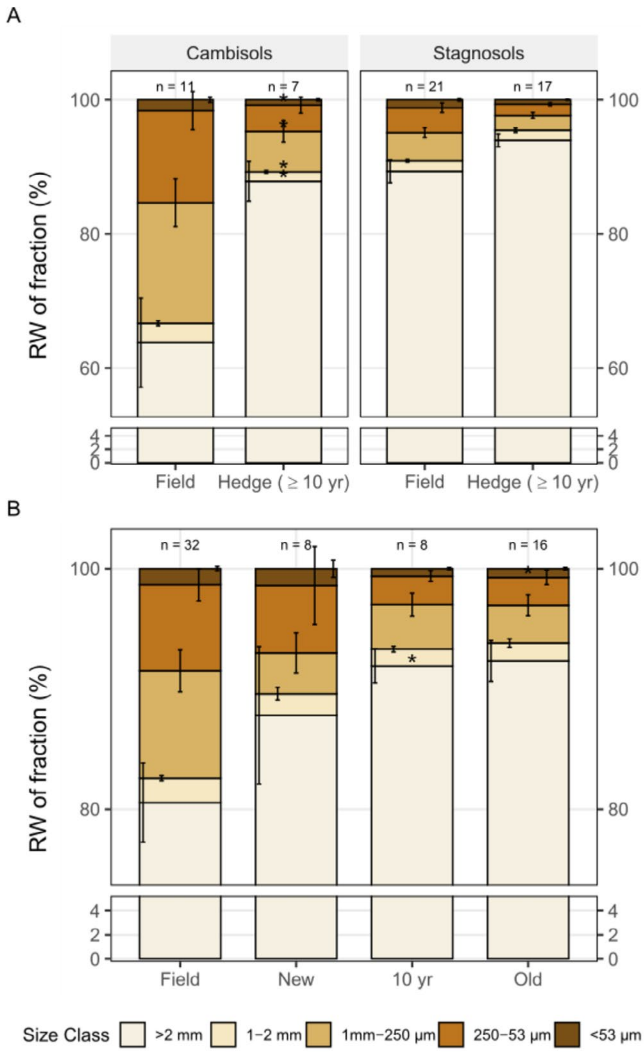

FIGURE 6 | Mean (± SE) contribution of each of the five soil aggregate size fractions and their relative weight (RW) contribution to total soil mass at 0–10 cm depth under (A) hedges of 10 years and older and their adjacent grassland fields on cambisols and stagnosols and (B) hedges of different ages and their adjacent grassland fields across both soil groups. Asterisks indicate statistically significant differences in the relative weight of a particular aggregate size class between hedges and fields, according to (A) Wilcoxon tests and (B) post hoc Dunn's tests ($\alpha < 0.05$). No significant differences were observed between different hedge age categories.

Manrique and Jones 1991). Vopravil et al. (2020) compared these soil properties among six soil groups and, similarly to our study, found significantly higher porosity in stagnosols than in cambisols, and significantly lower particle density. Asmall study in Northern England, also found that hedges increased soil porosity compared to adjacent grassland fields, and that a site on stagnosol had a mean porosity higher than a site on cambisol (Webb 2021). To compare our soil porosity results to typical values in the UK, we calculated the porosity of soils collected on mineral soils as part of the 2019 Countryside Survey (Robinson et al. 2020; Smart et al. 2020; Bentley et al. 2023), following Ruehlmann (2020) and Thomas et al. (2024) (details in Data S7). Soil porosity at 0–15 cm depth across the UK was on average 0.54, 0.58 and 0.61 cm cm^{-3} in arable, improved grassland, and broadleaf woodland, respectively. In our study, soil porosity at 0–10 cm depth in predominantly grassland fields and under hedges was 0.51 and 0.60 cm cm^{-3}, respectively, highlighting that porosity in the topsoil under hedges is comparable to that of woodland soils.

The SOC content was also influenced by the reference soil group, as we found the silt and clay-rich stagnosols to have significantly higher SOC content than the sand-rich cambisols. Soil texture plays a crucial role in the capacity of a soil to store SOC, as the majority of SOC is bound to the fine mineral fractions of silt and clay (Laganière et al. 2010; Plaza et al. 2013). Moreover, soil pH influences SOC by affecting SOM mineralization rates (Aciego Pietri and Brookes 2008) and stagnosols had a marginally but significantly higher pH than cambisols. It should be noted that the difference in SOC content does not result in a difference in additional SOC stock under hedges on stagnosols compared to hedges on cambisols. Using the data on SOC stock under the same hedges used in this study (publication: Biffi et al. 2022, dataset: Biffi et al. 2024b), we calculated the additional SOC stock (ΔSOC_{stock}) with equivalent soil mass correction at 0–50 cm depth under hedges compared to adjacent fields in cambisols and stagnosols after excluding new hedges. ΔSOC_{stock} under hedges on cambisols ($n = 7$) was 35.2 ± 41.7 Mg C ha^{-1} and was not significantly different from ΔSOC_{stock} under hedges on stagnosols ($n = 17$), which was 59.4 ± 66.9 Mg C ha^{-1}. These results support the findings from Biffi et al. (2025), which showed that hedgerows across different pedoclimatic conditions in the UK stored consistent additional SOC stock compared to grassland fields, which on average is ~40 Mg C ha^{-1} at 0–50 cm depth. Moreover, Biffi et al. (2025) showed that this additional SOC stock was associated with the particulate organic matter (POM) fraction, which, as opposed to mineral associated organic matter (MAOM) is not related to soil texture or other soil physical properties.

4.2 | Impact of Hedgerows on Saturated Hydraulic Conductivity and Influence of Soil Group

We found that K_{sat} was higher under hedgerows than adjacent grass fields. Our study corroborates and extends recent research demonstrating that hedgerows have significant larger rates of K_{sat} than adjacent agricultural land on both grassland and arable land use as a result of better soil structure (Holden et al. 2019; Kingsbury-Smith et al. 2023). Holden et al. (2019) assessed K_{sat} in grassland fields and under hedges on cambisols ($K_{sat} = 0.49$ mm h^{-1}), and our results ($K_{sat} = 0.97$ mm h^{-1}) were consistent with their findings. However, K_{sat} under hedges in our study (51.6 mm h^{-1}) was higher than the 19.4 mm h^{-1} reported in (Holden et al. 2019), but was of a similar order of magnitude as the 60 times increase in infiltration rates reported as a result of planting shelterbelts on cambisol pastures (Carroll et al. 2004). It should be noted that our findings are for intensively managed grasslands that are cut and grazed, and are therefore more likely to have lower infiltration rate than upland semi-natural grassland fields (Sochorec et al. 2015), we thus present the greatest expected differences in infiltration between fields and hedges in the Eden Catchment.

Soil reference group had a strong influence on K_{sat}, as K_{sat} of grassland fields on cambisols was ten times higher than fields

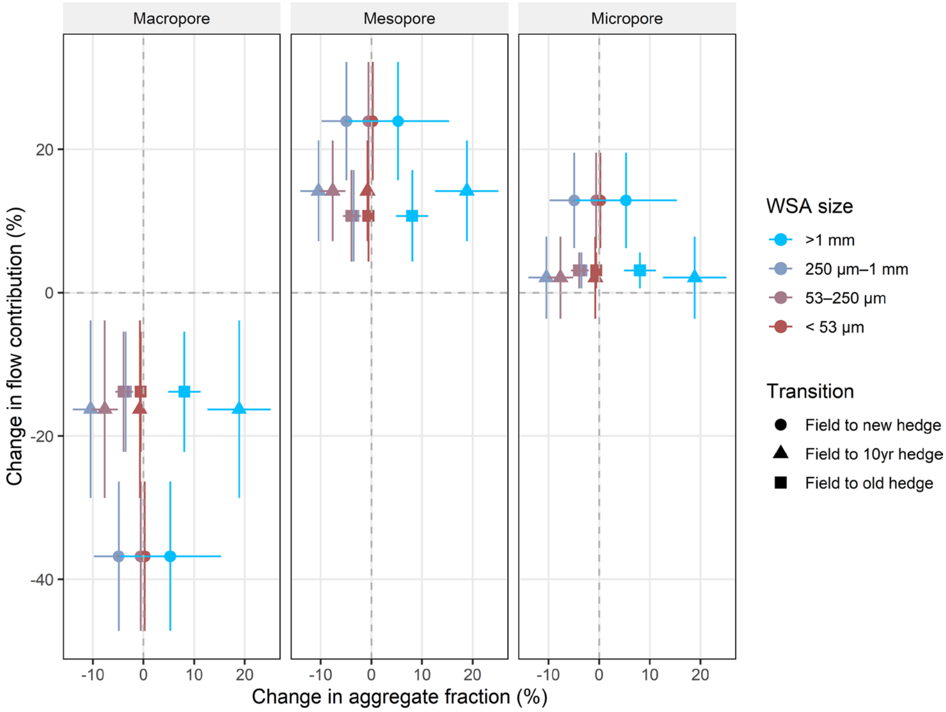

FIGURE 7 | Bivariate plots of the change in relative weight of different soil aggregate fractions in the top 10 cm of soil (> 1 mm, 250 μm–1 mm, 53–250 μm and < 53 μm, %) against the corresponding change in flow contribution (%) across three pore sizes (macropores > 1 mm, mesopores 0.5–1 mm, micropores 0.25–0.5 mm). Points represent mean differences (± SE) between paired samples of hedgerow and adjacent field soils, stratified by land-use transition stage (new, 10-year and old hedges).

on stagnosols, a result also shown in the linear models of log-transformed K_{sat}. In both soil groups, K_{sat} was significantly larger under hedgerows compared to adjacent fields, but the magnitude of change was considerably larger on cambisols than on stagnosols, suggesting that hedgerows may have a more positive effect on flood risk reduction when they are planted on soils with good drainage, such as cambisols, compared than when they are planted on poorly draining soils, such as stagnosols. Despite being positively associated with SOC content, K_{sat} was negatively associated with clay content, a result in line with recent studies on soil hydrological properties of different soil types (Usowicz and Lipiec 2021; Horn et al. 2020). Moreover, we suggest that the rate of increase in infiltration rate associated with planting hedges will occur over a longer timeframe for stagnosols than cambisols, as new hedges were not significantly different from fields on stagnosols, whereas they were for cambisols. Overall, our results show that hedgerow planting on poorly draining soil has a smaller effect on their natural flood mitigation potential, and that this contribution occurs over a longer timeframe compared to well-draining soils.

4.3 | Impact of Hedgerows on Water Flow Through Pores of Different Sizes

Our results show that unsaturated hydraulic conductivity (K) was higher under hedgerows than in adjacent fields, and that the increase in infiltration is due to the presence of a wider range of pore sizes under hedges, which is representative of a better soil structure. We found that the contribution of meso- (0.5–1 mm) and micropores (0.25–0.5 mm) to flow significantly increased in soil under hedges compared to adjacent grassland fields, while the contribution of macropores (> 1 mm) decreased, and that this difference remained significant when looking at sites on stagnosols throughout the different hedge age classes. Our results align with those of Holden et al. (2019), who found that soil under hedgerows was associated with a higher proportion of pores with a diameter < 0.25 and 0.25–0.5 mm, and that pastures were associated with a greater proportion of soil pores > 1 mm in diameter. Healthier soils usually exhibit a more complex and heterogeneous pore network, which enhances water holding capacity, aeration and microbial activity (de Oliveira et al. 2022; Pires et al. 2022). This is also linked to soil type, as soil texture can affect the formation of soil aggregates and, therefore, of soil pores (Zhang and Li 2010).

Intensive land management can reduce the proportion of smaller pores through compaction and SOC depletion, reducing water retention capacity (Dlapa et al. 2020). Although grassland soils may present a greater proportion of large pores, this is not associated with improved infiltration rates (as shown by our K_{sat} results). This is unsurprising, as, for example, Alaoui et al. (2011) showed that pores in forested soils are more efficient for water flow than those in pastures due to differences in pore structure and connectivity. The POM-rich soil under hedges (Biffi et al. 2025) and its improved soil biology, particularly in clay-rich stagnosols, is associated with a range in pore sizes, which allows the soil to retain water for longer within meso- and micropores, while also improving overall infiltration rates. Soil pore distribution of hedges planted on stagnosols did not change significantly among age classes. This may be because all hedges, including newly planted ones, were placed on historical hedgerow boundaries (Biffi et al. 2022).

4.4 | Impact of Hedgerows on Water Stable Aggregates Distribution and Influence on Soil Group

Our results showed that soil under hedges had a higher proportion of large macroaggregates (> 2 mm), and a lower proportion of medium macroaggregates (1–2 mm), small macroaggregates (250 μm–1 mm) and microaggregates (53–250 μm) compared to adjacent grassland fields. Soil reference group had a strong influence on these properties, with hedges planted on cambisols having more aggregates > 2 mm and fewer aggregates 2 mm–53 μm, whereas although the trend in change in aggregate size distribution was similar for stagnosols, it was not significant between hedges and fields. Soil type can affect soil aggregation, as the rate and stability of this process generally increases with SOC and with clay content (Bronick and Lal 2005; Ciric et al. 2012). Thus, it is not surprising that stagnosols, which were higher in both properties showed smaller (and non-significant) differences in the distribution of aggregates between hedges and fields compared to cambisols.

Improved soil biology under hedges is likely responsible for the improved soil structure (Lehmann et al. 2017), as SOM decomposition has been directly linked to the formation of soil aggregates (Bucka et al. 2019). During the decomposition of POM, gel-like components released by the soil microbiota combine with POM residues high in lignin, facilitating the formation of soil macroaggregates (Feng et al. 2024; Ding et al. 2025). Our results align with the findings of Guest et al. (2022) that found that hedges on cambisols had a significantly higher proportion of macroaggregates compared to arable fields. These results suggest that soil biology under hedgerows differs to that of silvopastoral agroforestry systems, as Fornara et al. (2018) found that soil under ash tree silvopastoral systems (planted at 400 and 2500 stems ha^{-1}) was higher in aggregates 2 mm–53 μm and < 53 μm compared to adjacent perennial ryegrass pasture at 0–10 cm depth. Wenzel et al. (2023) showed that the macroaggregate fraction under hedges (2 mm–200 μm) also stored more SOC than the equivalent fraction in arable soils. Evidence from long-term forest succession studies also indicate that fine roots contribute disproportionately to SOC accumulation within macroaggregates compared to litter (Shi et al. 2023). However, the role of root systems to SOC dynamics under hedges remains poorly understood and should be explored further.

4.5 | Implications of Finding for Policy and Modelling of NBS

We found that hedgerow planting resulted in a change in soil structure, shifting the distribution of soil aggregates towards large macroaggregates, which was linked to a marked decrease in macropore flow and an increase in micro- and mesopore flow and soil porosity, a result shown in other afforestation studies (Carroll et al. 2004; Holubík et al. 2014; Holden et al. 2019). These results suggest a functional reorganisation of soil structure that may favour stable infiltration patterns through small pores and increase water holding capacity under hedges. Soil under hedges had a larger proportion of smaller soil pores compared to adjacent grassland; however, even with a high proportion of small pores, a soil with good structure and aggregation (where soil particles aggregate together) can have improved infiltration, as the larger soil aggregates under hedges allow for better water movement (Alaoui et al. 2011). The increased SOM under hedges binds soil particles together into stable aggregates, increasing porosity and infiltration and likely increasing water holding capacity (not measured in this study). Moreover, soils under hedges have high SOM content, providing good habitat for soil biota, such as earthworms that increase pore space and connectivity, linking the upper soil layer to subsurface layers (Hallam et al. 2021).

The soil reference group on which hedgerows are planted strongly affects the hydrological properties of soils under hedges. Although planting has a positive effect on SOM and SOC content, and on soil aggregation, resulting in improved infiltration rates for both soil groups, the impact on K_{sat} was greater for cambisols than for stagnosols, despite the latter having higher SOM content (due to high clay content), which resulted in a higher proportion of large aggregates and increased flow through micro and meso pores that can hold water for longer. Change in infiltration rates appeared to take more time for stagnosols than cambisols, as 10-year hedges on stagnosols did not show significant differences from fields, whereas they did for cambisols. Thus, our results show that hedgerow planting on these two soil reference groups has the potential to contribute to flood risk alleviation, but that the effects of hedges on soil hydrological properties will be higher on well-draining soils than in poorly draining ones. Cumbria has experienced several well-documented flooding events in recent decades (Sibley 2010; Mathews and Hardman 2017), and natural flood management has been widely recommended as part of a strategy to reduce the impacts of such extreme events (Huq and Stubbings 2015; Cumbria Woodlands 2025; West Cumbria Rivers Trust 2025). Our findings suggest that hedgerows can play a role in improving soil hydrological functioning within a broader catchment-scale approach. However, their placement in the landscape should be informed by catchment conditions, with targeted action based on soil type; hedgerows planted on well-draining upstream cambisols are likely to have a more pronounced effect on downstream flooding.

To our knowledge, no modelling studies have used different K_{sat} values for different soil types, and our results therefore provide data for model parametrisation to account for differences in effectiveness depending on hedgerow location, potentially reducing uncertainty in predictions (Carrick et al. 2019). Finally, our results show that existing hedges in agricultural land in the Eden catchment are not preferentially oriented parallel or perpendicular to slopes. Linear woody features should be planted perpendicular to slopes to work as interceptors and have an impact on runoff at the catchment scale (Lashford et al. 2022). Thus, our results suggest that new hedgerow planting schemes in the catchment should be preferentially planted across slopes. However, hedgerows deliver multiple ecosystem services in agricultural landscapes (Froidevaux et al. 2019; Holden et al. 2019; Litza et al. 2022; Drexler and Don 2024; Biffi et al. 2024a, 2025) and the conservation of existing hedgerows should remain a priority (Staley et al. 2023).

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used in this publication is accessible on Zenodo DOI 10.5281/zenodo.16912309.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** sum70179-sup-0001-Supinfo.docx.