Soil type and land use effects on tensorial properties of saturated hydraulic conductivity in northern Germany

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Abstract
Long-term soil management can produce anisotropic impacts on soil structure, resulting in differences in horizontal and vertical hydraulic conductivity. As limited data exist on these impacts, this study provides a broad-scale assessment across 764 soil profiles under arable and grassland use in northern Germany (Federal State: Schleswig-Holstein). The soils were sampled in the four geological regions: Weichselian glacial region, the sandy outwash region (Lower “Geest”), the Saalian glacial region (Higher “Geest”) and the marshland with alluvial deposits. Saturated hydraulic conductivity (Ks) either in a horizontal (Ks_h) or vertical direction (Ks_v)) and the pore-size distribution were determined on undisturbed soil samples (100 cm³), whereas the grain size distribution was analysed on disturbed samples from the major soil horizons. This research work presents Ks_h and Ks_v values for representative soil types of the four geological regions down to a depth of 60 cm. Irrespective of the parent material in the four geological regions, arable soils showed a pronounced anisotropy of Ks in the horizontal direction. However, Ks_h and Ks_v also showed a high variability across the geological regions from approximately 1 to 800 cm d⁻¹, whereas the ratio of Ks_h to Ks_v ranged from 0.1 to 500. In the marshland (dominated by Gleysols), the direction-dependent values were superimposed by sedimentation processes of the marine material and/or structural development processes such as vertical shrinkage or bioturbation processes. Under grassland, the topsoils primarily indicated horizontally anisotropic flow conditions. In the “Geest” area with a high share of dairy farming, both top- and subsoils displayed the highest horizontal anisotropy values, indicating the stress-induced formation of a platy structure caused by trampling, grass harvesting or slurry application with heavy machinery. Soil type (e.g., Stagnic Luvisols, Stagnosols or Anthrosols) and horizon-dependent horizontal anisotropy were also more pronounced in arable than in grassland subsoils.

Highlights
- Hydraulic conductivity in arable subsoils shows mostly horizontal behaviour.
- Hydraulic conductivity in grassland topsoils shows mostly horizontal behaviour.
- The anisotropic degree and its direction depend on land use type and clay content of the soils.
INTRODUCTION

Land-use management and tillage affect soil structure and its impact on water transport. Poor practices lead to nutrient leaching, surface runoff and poor conditions for root growth (Bertolino et al., 2010; Dörner & Horn, 2006; Jones, Spoor, & Thomasson, 2003).

Although research has explored bulk changes in porosity and pore-size distribution to quantify their effects on land management (Ball et al. 1994, Lipiec, Kus, Słowinska-Jurkiewicz, & Nosalewicz, 2006, Çerçioğlu, Anderson, Udawatta, & Alagele, 2019), differentiation between vertical and horizontal flow, indicating anisotropic flow, has been poorly studied (Dörner & Horn, 2006, 2009; Santos & Esquivel, 2018). Mualem (1984) discussed the effect of particle arrangement on water fluxes and defined the degree of anisotropy as an expression of the tensor function. Often this degree of anisotropy is defined as the ratio of horizontal to vertical flux properties in soils, whereas the intermediate direction is ignored for reasons of simplicity (for more details see also Boñe, 2005). Tigges (2000) and Dörner (2005) determined the complete tensor function of hydraulic conductivity as a function of matric potential in differently aggregated soils derived from glacial till and under conventional and conservation tillage. They defined anisotropy based on aggregate type and effects of pre-drying. Furthermore, Dörner and Horn (2006, 2009) linked anisotropy of hydraulic conductivity with the maximum drying intensity (= most negative matric potential) in order to consider the effect of structural rigidity and its changes on pore functions. These links are essential for (amongst other things) water flux modelling, because exceeding the internal soil strength due to mechanical, hydraulic or even physicochemical stresses results in an additional particle and pore rearrangement due to proportional shrinkage (Horn, Peng, Fleige, & Dörner, 2014).

The well-known multidimensional fluxes in structured soils (Vogel, Gerke, Zhang, & Van Genuchten, 2000) can be caused by varying particle sedimentation (Buczko, Gerke, & Hüttl, 2001; Ritsema & Dekker, 1994), anthropogenic constructions (e.g., waste deposit sealing layers) (Beck-Broichsitter, Feige, & Horn, 2017; Widomska et al., 2015), glacial processes (Hartge & Horn, 2016), chemical precipitation or biological processes (Rogasik, Schrader, Onasch, Kiesel, & Gerke, 2014). Soil tillage and induced stress–strain processes result in soil deformation and the formation of a platy structure with pronounced differences in flow intensity and directions (Alaoui, Lipiec, & Gerke, 2011; Babel, Benecke, Hartge, Horn, & Wiechmann, 1995; Hartge & Horn, 2016; Horn, Fleige, Zimmermann, & Peng, 2017; Mordhorst, Peth, & Horn, 2014). Dörner and Horn (2009), Dörner, Dec, Zuniga, Sandval, and Horn (2011), Berisso et al. (2013) and Horn (2015) documented the consequences for fluxes, not only with respect to the intensity but also the directions. They also discussed the question of reduced resilience and limited sustainability. Recently, Rogger et al. (2017) and Alaoui, Rogger, Peth, and Blöschl (2018) related the effects of soil compaction and land use to landscape flooding, including massive off-site soil erosion. They identified changes in flow directions due to platy structure and linked them to large-scale soil or landscape degradation. How far such changes can be detected on a large scale with various geological origins and soil properties is still unknown. Thus, it is the aim of this paper to analyse datasets covering a large area (the entire Federal state Schleswig-Holstein). We hypothesize that: anthropogenic processes in soils (soil compaction caused by heavy machinery during tillage, grass harvesting or slurry application, or trampling of grazing animals) alter the degree of anisotropy of the saturated hydraulic conductivity; therefore, saturated hydraulic conductivity at various depths is affected by the land use, soil type and parent material (clay content).

MATERIAL AND METHODS

The data were collected over the last 45 years by the State Agency for Agriculture, Environment and Rural Areas of the German Federal State Schleswig-Holstein (LLUR) as well as its predecessor agencies during various research programmes in Schleswig-Holstein. In total, 764 soil profiles were collected and a complete soil type description, including physical and chemical data down to at least the 60-cm depth under arable land and grassland use (at the time of sampling), was obtained. Note that both land use types include various soil management systems, such as conventional (ploughing) and conservation tillage systems, as well as pasture and meadow systems of different intensities, which are summarized by the terms “arable land” and “grassland”, respectively. The soil samples were collected in the four geological regions of Schleswig-Holstein: the Weichselian glacial region in the east, the sandy outwash region (Lower “Geest”), the Saalian glacial region (Higher “Geest”) in the centre, and the marshland with alluvial
deposits in the west. The Weichselian glacial deposits contain not only very fertile Luvisols, Cambisols and Anthrosols derived from colluvic material, but also Gleysoils and Rheic Histosols. The outwash region is dominated by Brunici Arenosols or Cambisols (depending on soil texture), Podzols and Gleysoils, as well as Histosols. The Saalian glacial region is characterized by mainly loamy and sandy carbonate-free Brunici Arenosols or Cambisols, Stagnosols, Podzols, Gleysoils and Rheic Histosols. Finally, the marshland includes different types of Fluvic Gleysoils and Histosols. The areas of the four regions are as follows: marsh region, 2,854 km²; sandy outwash region, 2,010 km²; Saalian glacial region, 3,766 km²; Weichselian glacial region, 6,740 km².

Saturated hydraulic conductivity (Ks), bulk density and air capacity (AC) (air-filled pore volume at -6 kPa) were determined on undisturbed soil samples (100 cm³), whereas grain size distribution was analysed on disturbed samples. In this paper, the data on the Ks patterns were included down to the 60-cm depth from all soil profiles. The undisturbed soil cores for the determination of the saturated hydraulic conductivity were taken only in one direction, either vertically or horizontally, depending on the corresponding research questions or scientific recommendations in those days. However, over the decades the dominant soil types in the various regions were sampled repeatedly (but not at the same site) and this led to the nearly identical number of Ks values for both sampling directions. The test method for analysing the saturated hydraulic conductivity was almost identical throughout the decades (falling head method according to Hartge, 1966 and Kretzschmar, 1996). The presented data are the geometric mean for the various soil profiles and land-use types. They are the basis for the quantification of two out of the three main components of the tensor. Ks values were evaluated according to the German soil classification system (Ad-hoc-AG Boden, 2005; Horn & Fleige, 2003). Air capacity was derived from the water-retention functions and corresponds to the amount of wide, coarse pores > 50 μm, representing the soil water content at field capacity at -6 kPa according to the German soil classification system (Ad-hoc-AG Boden, 2005, Horn & Fleige 2003); for more methodical details see Blume et al. (2010) and Hartge & Horn (2016).

The statistical software R (R Core Team, 2018) was used to evaluate the data. The data evaluation started with the definition of an appropriate statistical model based on generalized least squares (Carroll & Ruppert, 1988). The Ks data was lognormal distributed and heteroscedastic. These observations are based on a graphical residual analysis. The statistical model included the tested factors like sampling direction (Ks_h and Ks_v), clay content class (<12 and ≥12% clay), land use type (arable and grassland), depth (topsoil, subsoil ≤40 cm and ≤60 cm, respectively) and parent material represented by the geological region (Weichselian glacial area, Lower “Geest”, Higher “Geest”, Marshland). The clay content classes “<12” and “≥12%” were chosen because aggregate formation and coinciding effects on pore

**FIGURE 1** Effect of clay content, bulk density and air capacity (AC) on the vertical saturated hydraulic conductivity (Ks_v) for all corresponding top- and subsoils (≤60 cm depth) in Schleswig Holstein with clay contents < and ≥12%; n = total number of soil profiles
functions are more visible after exceeding this clay limit (Horn 1981, Blume et al. 2016). An analysis of variance (ANOVA) was conducted, followed multiple contrast tests for the $K_s$ values. Significant differences between the $K_s$ values of different sampling direction and the clay content class were calculated with a significance level of 0.05.

\section*{RESULTS}

Figure 1 shows the saturated hydraulic conductivity in the vertical direction ($K_{sv}$) for all soils down to the 60-cm depth as a function of the clay content, the bulk density and the AC. The $K_{sv}$ values are more closely linked to clay content and AC for soils $< 12\%$ clay, whereas these relationships diminish with higher clay content ($\geq 12\%$ clay). In contrast, $K_{sv}$ values show no influence of bulk density for soils either with $< 12\%$ clay or with $\geq 12\%$ clay. However, there is also no correlation between these parameters if only subsoil data (no ploughing effects) are analysed (data not shown).

Figure 2 summarizes the data for $K_s$ values both in vertical ($K_{sv}$) and horizontal ($K_{sh}$) directions down to $\leq 40$-cm depth in the four geological regions. Irrespective of the geological origin of the samples, and for both texture classes (clay $< 12\%$ and $\geq 12\%$), we find significantly greater $K_{sh}$ than $K_{sv}$ values under arable land use ($P < 0.01$). $K_{sh}$ and $K_{sv}$ values decrease significantly with higher clay content ($\geq 12\%$) irrespective of sample direction ($P < 0.001$). The direction-dependent saturated hydraulic conductivity documents a pronounced anisotropy under arable land use below the tilled A-horizon, and this is reflected by higher $K_{sh}$ than $K_{sv}$ values (subsoil $\leq 40$-cm depth). The data from the ploughed A horizons were not suitable for the evaluation of anisotropy patterns because the dataset did not include information on the timespan between sampling and ploughing (i.e., homogenization). If we compare all arable and grassland sites concerning the anisotropy patterns as a function of the clay content, it becomes obvious that the $K_{sh}$ dominates in the subsoil horizons under arable
TABLE 1  Horizontal ($K_{h}$) and vertical hydraulic conductivity ($K_{v}$) of arable subsoils (≤ 40 cm; ≤ 60 cm depth) with clay contents < 12% and ≥ 12% in the geological regions of Schleswig-Holstein

| Soil horizon; depth | Geographical region       | Soils < 12% clay | Soils ≥ 12% clay | h/v     | Soils < 12% clay | Soils ≥ 12% clay | h/v     | Soils < 12% clay | Soils ≥ 12% clay | h/v     |
|---------------------|---------------------------|------------------|------------------|---------|------------------|------------------|---------|------------------|------------------|---------|
|                     |                           | Horizontal ($)   | Vertical ($)     | Anisotropy ($) | Horizontal ($)   | Vertical ($)     | Anisotropy ($) | Horizontal ($)   | Vertical ($)     | Anisotropy ($) |
|                     | Mean clay content (%)     | Mean $K_{h}$ ($cm d^{-1}$) | Mean clay content (%) | Mean $K_{v}$ ($cm d^{-1}$) | n (--) | Mean clay content (%) | Mean $K_{h}$ ($cm d^{-1}$) | Mean $K_{v}$ ($cm d^{-1}$) | n (--) | Anisotropy ($) | Mean clay content (%) | Mean $K_{h}$ ($cm d^{-1}$) | Mean $K_{v}$ ($cm d^{-1}$) | n (--) | Anisotropy ($) |
| Subsoil horizons ≤ 40 cm | Weichselian glacial area | 6.3 105.7 aA | 5.4 30.8 aA | 6 3.4 | 21.5 7.8 aA | 29 24.3 1.9 aA | 12 4.0 |
| Lower “Geest” | n.v. | n.v. | n.v. | n.v. | n.v. | n.v. | n.v. | n.v. | n.v. | 10 25.8 aA | 3.8 127.3 aA | 10 2.0 | n.v. | n.v. | n.v. | n.v. | n.v. | 5 25.4 |
| Higher “Geest” | 5.3 177.7 aA | 5.3 28.2 aA | 11 6.3 | 20.2 14.2 aA | 3 17.0 0.6 aB | 5 25.4 |
| Marshland | n.v. | n.v. | n.v. | 8.2 3.6 A | 6 n.v. | 23.1 0.9 a | 6 28.5 1.0 aA | 32 0.9 |
| Total | 6.1 112.8 29 | 6.0 17.3 27 | 6.5 | 21.5 6.1 | 39 26.1 1.2 | 50 4.9 |
| Subsoil horizons ≤ 60 cm | Weichselian glacial area | 6.1 89.7 aA | 5.4 53.5 aA | 16 1.7 | 22.1 6.2 aB | 89 23.8 7.1 aB | 38 0.9 |
| Lower “Geest” | 3.6 259.8 a | 3.8 127.3 aA | 10 2.0 | n.v. | n.v. | n.v. | 14.1 14.1 aA | 3 n.v. |
| Higher “Geest” | 5.6 119.0 aA | 5.7 43.6 aA | 48 2.7 | 17.8 12.4 aB | 17 18.6 1.2 bB | 22 10.2 |
| Marshland | 9.2 9.0 aA | 8.5 7.2 aA | 17 1.3 | 23.6 0.7 aA | 13 29.1 1.1 aB | 73 0.7 |
| Total | 5.9 90.6 88 | 6.0 36.0 91 | 2.5 | 21.6 5.6 | 121 25.6 2.0 | 136 2.8 |

n = number of samples (in italics), anisotropy = ratio between horizontal to vertical $K_{v}$ values (geometric mean) (in bold), n.v. = no values (n < 3). Significant differences between $K_{h}$ and $K_{v}$ values are denoted by lowercase letters (ab), those between clay content classes by uppercase letters (AB), with a significance level of 0.05.
land use for both texture classes. Therefore, the level of $K_s$ values decreased with higher clay content, resulting in a distinct reduction to low and very low values (< 10 cm d$^{-1}$) in the vertical direction ($K_{s\_v}$). In contrast, for the grassland sites a horizontal anisotropy is most obvious for the topsoil (significantly for soils < 12% clay, $P < 0.001$) and less pronounced for subsoil horizons down to the 40-cm depth (Figure 2). Grassland subsols with a clay content $\geq 12\%$ even show a higher hydraulic conductivity in the vertical ($K_{s\_v}$) than in the horizontal direction ($K_{s\_h}$) ($P < 0.05$).

For the arable subsoil horizons $\leq 40$-cm depth, the horizontal anisotropy (with a ratio of $K_{s\_h}$ to $K_{s\_v} > 3$) is very pronounced and decreases for samples taken at the $\leq 60$-cm depth ($< 3$) (Table 1). This was especially true for arable subsoil horizons with a clay content $\geq 12\%$ from the Weichselian glacial area, because anisotropy turns from a preferentially horizontal direction for the $\leq 40$-cm depth (below the plough pan) to a vertical direction for the $\leq 60$-cm depth. These depth-specific changes are more intense the higher the clay content is. Thus, if we include all samples from the complete soil profiles down to the 60-cm depth, the loamier Higher “Geest” sites show a significant pronounced horizontal anisotropy (mean value of 25, $P < 0.05$), whereas the marshland soils with $\geq 12\%$ clay have a higher $K_{s\_v}$ than $K_{s\_h}$ ($K_{s\_h}$/ $K_{s\_v} = 0.2-0.9$).

The grassland sites (Table 2) reveal notable differences compared to the arable sites (Table 1). Here, the horizontal anisotropy almost dominates in the top- and subsoil horizons of the “Geest” soil profiles even within $\leq 60$-cm depth. However, the highest $K_{s\_h}$ (> 800 cm d$^{-1}$) and highest degree of anisotropy (> 500) were found in the lower “Geest” region in the grassland subsols with higher clay content ($\geq 12\%$); it should be noted that these finer-textured soils are not representative for this region with mostly sand-dominated soils resulting in a low sampling frequency ($n < 6$).

The data reveal that with increasing clay content the horizontal anisotropy could be detected more often, especially in the Higher “Geest” sites. In contrast, grassland soils from the Weichselian glacial area (not significant) and the marshlands ($P < 0.05$) indicate mostly a vertically anisotropic flux behaviour.

The detailed analysis of various soil types underlines the existence of an apparently more platy structure in the clay-depleted Eg horizon of the Stagnic Luvisols under arable land use, whereas the sandier Cambisols or Podzols show isotropic flow conditions (Figure 3). Mean $K_s$ values of Ah horizons of Anthrosols and Bg/Cg horizons of Stagnosols also tend to anisotropy in the horizontal direction, which is more pronounced under arable land use than grassland. Cl horizons of Gleysols in the marsh region have a more pronounced vertical flow direction down to the 60-cm depth. A more detailed analysis of the shallow subsoil horizons at $\leq 40$-cm depth was not possible because the number of replicates was too small.

4 | DISCUSSION

Between internal soil parameters, such as texture, aggregation, actual strength, bulk density and pore continuity, and externally applied chemical, physical and anthropogenic stresses are straight links, which are responsible for soil degradation (Horn & Peth, 2011). It is well known that the greater the clay content, the more pronounced is the swelling and shrinkage-induced aggregate formation, which starts with a prismatic structure, and vertical cracking dominates. Thus, the dominating fluxes are vertical, whereas, due to consecutive shearing, polyhedral and subangular blocks are formed with more pronounced isotropic fluxes and pore connectivity. In this context, the limit for structure-relevant clay content is set at 12%, as soils with lower clay contents (< 12%) are not able to form a strong skeletal structure through aggregation; the grain matrix and corresponding primary pore system dominate all internal soil functions (Blume et al., 2016). Hence, the influence of clay content and air capacity on the vertical hydraulic conductivity ($K_{s\_v}$) diminishes with higher clay content ($\geq 12\%$ clay) due to these natural structure formation processes and the development of a secondary pore system (see Figure 1). Thus, the often-assumed link between the bulk density and $K_{s\_v}$ cannot be detected for the whole soil profile or for the subsoil horizons for either clay content groups. This is not surprising, because bulk density only defines a soil mass per volume, but not how or where the mass or the pores are arranged in a given volume and how far these pores are interconnected with each other (Bohne, 2005; Hartge & Horn, 2016). Thus, especially in aggregated soils, the intense scattering of datasets is to be expected; they had a wide range of bulk density values. The majority of bulk density values range between medium (1.4 g cm$^{-3}$) and high (1.8 g cm$^{-3}$) because of the geological origin and the effect of soil tillage in the subsoils below the ploughed A horizon. The alteration of these natural aggregate types is caused by soil tillage. Stress application with tillage causes particle rearrangement, and this causes a platy structure formation with dominating horizontal fluxes. The $K_s$ values are all in the medium (10–40 cm d$^{-1}$) to low (1–10 cm d$^{-1}$) or even very low (< 1 cm d$^{-1}$) range, and they are smaller the higher the clay content is. This range of $K_s$ values can be explained if the land use and tillage effects are considered. Soils with $\geq 12\%$ clay content have lower $K_{s\_v}$ values under arable land use, whereas coarser-textured soils show no pronounced differences between the two land use types.
| Soil horizon; depth | Geological region | Soils < 12% clay | Soils ≥ 12% clay |
|---------------------|-------------------|------------------|------------------|
|                     |                   | Horizontal (h)   | Vertical (v)     | h/v   | Horizontal (h)   | Vertical (v)     | h/v   |
|                     |                   | Mean clay content (%) | Mean Ks_h (cm d\(^-1\)) | n (--) | Mean clay content (%) | Mean Ks_v (cm d\(^-1\)) | n (--) | Anisotropy (--) | Mean clay content (%) | Mean Ks_h (cm d\(^-1\)) | n (--) | Mean clay content (%) | Mean Ks_v (cm d\(^-1\)) | n (--) | Anisotropy (--) |
| A horizons ≤ 40 cm  | Weichselian glacial area | 6.0  50.5 aA  28 | 6.9  85.4 aA  15 | 0.6  | 23.2  35.1 aA  23 | 22.1  30.8 aA  12 | 1.2  |
|                     | Lower “Geest”     | 5.8  125.4 a  12 | 4.5  36.4 a  24 | 3.4  | 17.3  62.7 aA  4 | 15.1  20 bA  8 | 31.9 |
|                     | Higher “Geest”    | 5.8  84.5 aA  36 | 6.8  12.6 bA  71 | 6.7  | 6.7  12.6 bA  4 | 15.1  20 bA  8 | 31.9 |
|                     | Marshland         | 7.5  6.6 aA  8  | 8.1  4.3 aA  7  | 1.5  | 28.1  1.9 aA  15 | 29.8  4.2 aA  45 | 0.5  |
|                     | Total             | 6.0  59.1 8 4  | 6.4  18.8 117  | 3.1  | 24.4  13.1 42  | 26.1  6.0 67  | 2.2  |
| Subsoil horizons ≤ 40 cm | Weichselian glacial area | 5.5  61.5 aA  14 | 6.3  151.6 aA  5 | 0.4  | 22.0  14.2 aB  10 | 28.2  19.6 aA  10 | 0.7  |
|                     | Lower “Geest”     | n.v.  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v  n.v | 1.0  | 21.5  3.8 aA  4 | 18.1  0.9 aB  11 | 4.1  |
|                     | Higher “Geest”    | 5.1  29.2 aA  6  | 5.0  28.7 aA  14 | 0.5  | 32.4  2.0 aA  46 | 32.8  11.6 bA  107 | 0.2  |
|                     | Marshland         | 9.2  4.7 aA  8  | 8.2  9.2 aA  14 | 0.5  | 32.4  2.0 aA  46 | 32.8  11.6 bA  107 | 0.2  |
|                     | Total             | 6.3  33.6 32 6  | 6.5  24.8 34  | 1.4  | 29.6  3.2 61  | 30.9  9.1 132  | 0.3  |
| Subsoil horizons ≤ 60 cm | Weichselian glacial area | 5.0  62.3 aA  22 | 6.6  105.8 aA  9 | 0.6  | 22.9  16.9 aA  27 | 27.4  18.9 aA  27 | 0.9  |
|                     | Lower “Geest”     | 3.7  402.6 aA  10 | 3.8  147.2 aA  12 | 2.7  | 15.6  822.9 aA  3 | 20.6  1.5 aB  6 | 552.0 |
|                     | Higher “Geest”    | 4.7  61.8 aA  15 | 5.5  18.1 aA  49 | 3.4  | 22.1  4.1 aA  8 | 19.1  1.1 aB  38 | 3.7  |
|                     | Marshland         | 8.2  3.6 aA  12  | 7.7  8.7 aA  30  | 0.4  | 33.2  1.8 aA  76  | 32.8  8.6 bA  186  | 0.2  |
|                     | Total             | 5.3  47.7 59 6  | 6.0  21.9 100  | 2.2  | 29.5  3.9 114  | 29.9  6.6 257  | 0.6  |

n = number of samples (in italics), anisotropy = ratio between horizontal to vertical Ks values (geometric mean) (in bold). n.v. = no values (n < 3). Significant differences between Ks_h and Ks_v values are denoted by lowercase letters (ab), those between clay content classes by uppercase letter (AB), with a significance level of 0.05.
FIGURE 3  Vertical ($K_{sv}$) and horizontal hydraulic conductivity ($K_{sh}$) of subsoil horizons ($\leq$ 60-cm depth) from representative soil types in Schleswig-Holstein under arable land (A) and grassland use (G); $n =$ number of samples. Significant differences between $K_{sv}$ and $K_{sh}$ values are denoted as lowercase letters (ab), those between land use types by uppercase letters (AB), with a significance level of 0.05
4.1 | Effect of pore arrangement and continuity on the dominant flow directions

Soil functions such as hydraulic conductivity, air permeability, gas diffusivity and thermal conductivity are all tensors with direction-dependent values. Structure formation especially alters the dominating flow directions and thus the degree of isotropy or anisotropy (Alaoui, Caduff, Gerke & Weingartner, 2011; Dörner, 2005; Dörner & Horn, 2006, 2009; Huang, Shao, & Tan, 2011). It is well known that soil horizons with prismatic structure like the Bt horizon of Luvisols exhibit a vertical anisotropy caused by the development of secondary pores (cracks). Mostly isotropic fluxes can be expected with a subangular blocky structure, whereas platy-structured horizons show a horizontal anisotropy (Hartge & Horn, 2016). A horizons with a biologically formed crumbly structure are often defined as macroscopically homogenous and show isotropic flow behaviour. However, our results document the effect of anthropogenic formation of plates, which alter the natural pedogenetic aggregate formation in top- (under grassland) and subsoils (predominantly under arable use). Only the C1 horizons of Gleysols from marshlands maintain their original anisotropy patterns with vertically orientated preferential flux direction down to the 60-cm depth, because drainage of excess soil water as well as a high biological activity supports vertical crack formation and the dominance of vertical fluxes, especially for grassland soils.

The results of the soil profiles under arable land use document a distinct horizontal anisotropy down to the 60-cm depth, whereas under grassland use, only soils from the “Geest” area, which are used for intense dairy farming and are, therefore, exposed to a high amount of trampling and wheeling, are characterized by a horizontal anisotropy. The dominant horizontal anisotropy of Ks under arable land use is generally caused by mechanical stress from tillage machines, which exceed the precompression stress or the preshrinkage stress range and cause the formation of new layers of plates down to deep depths. This occurs because repeated stress application causes primarily a plastic deformation and a horizontal crack formation due to the rearrangement of particles (Glinski, Horabik, & Lipiec, 2011; Holthusen, Brandt, Reichert, & Horn, 2018; Horn & Peth, 2011). Thus, a dominance of horizontal hydraulic conductivity is the visible sign of an intense soil degradation with consequences such as soil erosion or surface runoff and flooding (Rogger et al., 2017). Such interaction is also in agreement with the statements of Alaoui et al. (2018); they state that water runoff and surface soil erosion already occur with a higher frequency and have caused higher financial damages in recent years or even decades. Thus, reduction in nutrient uptake, deep-rooting, filtering and buffering, as well as enhanced rapid lateral water fluxes with coinciding soil erosion, are signs of degradation worldwide (Duttmann, Schwanebeck, Nolde, & Horn, 2014; Hartge & Horn, 2016). This general trend is also confirmed by the anisotropy data of topsoils under grassland, which show horizontally anisotropic flow conditions. Ajayi and Horn (2016), Holthusen et al. (2018), Alaoui, Caduff, Gerke and Weingartner (2011) and Zink (2009) describe similar findings. The glaciation effect on the Ks anisotropy in the Weichselian area of Schleswig-Holstein can most probably be ignored as an explanation for the horizontal anisotropy, because of the long-term weathering and subsequent structure formation due to swell shrinkage and biological processes in the relatively shallow soil depth. Such glacier stress-induced rearrangement of particles during the long-term, which has pushed mineral material over 10,000 years, can be visualized in soil depths of > 2 m only.

The most important question is how to ameliorate sites with pronounced horizontal anisotropy. Although detailed long-term studies on the time-dependent changes of the anisotropy ratio are missing in the literature, we need to consider its effect on the changes in functionality in order to prevent further soil degradation. Although methods like mechanical deep ploughing or soil loosening coincide with less dense soil layers, they deprive soils of their internal strength and, therefore, require altered soil management techniques with lighter machines in the coming decades or centuries. Furthermore, such loosening does not coincide with long-term increased and isotropic hydraulic or gaseous fluxes because of the destroyed pore continuity and the increased sensitivity to further soil settlement. Successful and environmentally appropriate alternatives are controlled traffic, partial deep loosening and careful land management. They all are better options for sustainable land use (Jayawardane & Stewart, 1994). Even more successful are biological amelioration techniques with long-term plantations of deep-rooted plants like alfalfa, especially in combination with conservation tillage systems that enhance earthworm activity. The existing literature on these topics under controlled environmental conditions is large, but in situ experiments with detailed physical and mechanical measurements, such as hydraulic conductivity, air permeability or stress-strain and derived precompression stress data, are hard to find.

5 | CONCLUSIONS

The results indicate that a preferentially horizontal flow behaviour (Ks_h > Ks_v) dominates in the subsoil horizons under arable land irrespective of the parent material in the geological regions of Schleswig-Holstein. The degree of such horizontal anisotropy increased with higher clay content (≥ 12% clay content) and was more pronounced below the plough pan (≤ 40-cm depth) than at greater depth (≤ 60 cm). A similar pattern was observed in top- and subsoils under grassland in the “Geest” regions with a high share of dairy farming. Horizontal anisotropy in both land-use systems could be explained by the stress-induced formation of a platy
structure resulting from repeated wheeling with heavy machines, trampling, grass harvesting or slurry application.

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DATA AVAILABILITY STATEMENT

Data are subject to third-party restrictions. The data that support the findings of this study are available from the State Agency for Agriculture, Environment and Rural Areas of the German Federal State Schleswig-Holstein (LLUR). Restrictions apply to the availability of these data, which were used under license for this study. Data are only available with the permission of the LLUR.

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