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Natural and anthropogenic compaction in North Germany (Schleswig-Holstein): Verification of harmful subsoil compactions

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Abstract

Many soil types in the federal state of Schleswig-Holstein (North Germany) are naturally compacted in the subsoil due to pedo- or geogenic processes (42% of the area) but, due to anthropogenic impacts, the percentage of subsoil compaction has increased further. To determine the overall subsoil compaction status of seven representative soil types in Schleswig-Holstein (≤ 60 cm depth), air capacity (AC), saturated hydraulic conductivity (K_s) and effective bulk density (ρ_{Beff}) of 342 soil profiles from the database of the State Agency for Agriculture, Environment and Rural Areas of Schleswig-Holstein (LLUR) were evaluated with respect to critical threshold values (AC < 5 Vol.-%, $K_s < 10$ cm day^{-1}, $\rho_{Beff} > 1.7$ g cm^{-3}). The compaction status was classified into Classes I–IV, where a harmful subsoil compaction was assumed if both values of AC and K_s simultaneously exceeded (are smaller than) their threshold value (Class IV). Subsoils of (Stagnic) Luvisols and Stagnosols derived from glacial till, as well as those of Fluvic Gleyic Stagnosols of the marshlands, showed a high degree of natural compaction (46%–65% in Class IV). In contrast, sandy subsoil horizons of Podzols and Brunic Arenosols derived from glacifluvial sediments were rarely compacted (< 13% in Class IV), and possessed the lowest ρ_{Beff}, which were similar to Anthrosols. Only 5%–18% of their subsoil horizons exceeded the critical value of 1.7 g cm^{-3}. Additionally, anthropogenic subsoil compaction of at least 6%–10% was verified for (Stagnic) Luvisols and Stagnosols.

KEYWORDS
air capacity, hydraulic conductivity, soil database, subsoil compaction

1 | INTRODUCTION

Soil compaction arises from natural (geo- or pedogenic) or anthropogenic processes. Pedogenic processes can cause compacted horizons like (petro-) duric, plinthic, calcic or gypsic horizons (Blume & Fleige, 2016), while in North Germany they mainly result from leaching and translocation of substances, like in the argic subsoil (Bt) horizon of Luvisols due to clay accumulation. This is accompanied by the reduction of macropores or the air capacity (AC), as well as the decrease in air permeability and saturated hydraulic conductivity (K_s) in the subsoil,

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which can cause stagnic conditions (Stagnosols) (Dörner & Horn, 2006; Hartmann, Zink, Fleige, & Horn, 2012; Menezes et al., 2018). Pedogenic processes, such as accumulation of iron/organic matter or iron/manganese, can also produce strongly cemented subsoil horizons (hardpans) of soil types like Ortsteinic Podzols or Gleysols (Petrogleyic), respectively. Needham, Scholz, and Moore (2004) listed several types of hard layers in soils developed by main processes, such as transient bonding, compaction, cementation and packing. Bryk (2016) analysed structural properties of B compared to underlying BC and C horizons of two Podzols, an Arenosol, a Luvisol and Cambisol and related their compaction degree to pedo- and geogenic processes. At sites under agricultural use, these compacted and root-limiting horizons have often been broken up by deep ploughing (Fleige et al., 2006).

Natural compaction that leads to stagnic conditions is also known in older marshland soils, such as the Fluvic Gleyic Stagnosols, which have a compacted fossil humic-rich horizon (called "Dwog") representing a former surface that was overlaid by marsh sediments in a subsequent transgression phase of the seawater level, or they are characterized by a clay-enriched, compacted horizon (called "Knick", often with $k_s < 1$ cm day^{-1}) as a result of geogenic (= layering) or pedogenic (= clay migration) processes (Janetzko & Fleige, 2010).

Anthropogenic soil compaction generally results from agricultural or forestry use due to machinery traffic, for example during tillage operations, spreading of fertilizers and pesticides, or harvesting on arable, grassland (including animal trampling), or forested soils. In the course of the increasing load of agricultural or forestry machines, the risk of subsoil compaction increases, because the applied loads often exceed the internal soil stability (normal stress > soil strength, Alakukku et al., 2003; Horn & Fleige, 2009; Horn & Peth, 2011; Riggert, Fleige, Kietz, Gaertig, & Horn, 2016; Zink, Fleige, & Horn, 2010). The irreversible soil deformation relates to changes in pore volume (e.g. decreasing air capacity, increasing bulk density) and pore geometry leading to the deterioration of pore functions (e.g. air and hydraulic conductivity) (Batey, 2009; Berisso et al., 2012; Gebhardt, Fleige, & Horn, 2009; Horn, Way, & Rostek, 2003; Pulido-Moncada, Munkholm, & Schjønning, 2019). At the profile scale, a compacted layer persisted as a plough pan (Bertolino et al., 2010; Mossadeghi-Björklund, Jarvis, Larsbo, Forkmann, & Keller, 2018), often linked with the formation of a platy structure accompanied with an anisotropic flux behaviour in the horizontal direction (Dörner & Horn, 2006, 2009). This impedes vertical water and air transport from top- to subsoil as well as root growth into deeper soil depths (Ehlers, Köpke, Hesse, & Böhm, 1983; Kuncoro, Koga, Satta, & Muto, 2014). Directly related negative impacts on crop productivity causing yield losses (Goeck, Cordsen, Geisler, & Blume, 1988; Hamza & Anderson, 2005; Keller,

Sandin, Colombi, Horn, & Or, 2019) were accompanied by increasing erosion risk due to enhanced surface runoff (Alaoui, Rogger, Peth, & Blöschl, 2018).

The intensity of soil use plays a crucial role in the extent of anthropogenic soil compaction in arable (Bertolino et al., 2010; Horn et al., 2003; Wiermann, Werner, Horn, Rostek, & Werner, 2000), grassland (Cui, Askari, & Holden, 2014; Holthusen et al., 2018; Koppi, Douglas, & Moran, 1992) and forest soils (Moffat, 1991; Riggert, Fleige, Kietz, Gaertig, & Horn, 2017). The influence of long-term soil management (arable and grassland use) on soil structure and related anisotropy properties of representative subsoil horizons in Schleswig-Holstein was investigated by Horn et al. (2019). They demonstrated that the horizontal anisotropy of hydraulic conductivity is not only soil type- and horizon-dependent, but also more pronounced in arable than in grassland subsoils. Compaction-induced structural damages in arable soils are primarily attributed to the soil below ploughing depth (≤ 40 cm depth), whereas grassland sites were more affected in the topsoil (Horn et al., 2019). Compared to topsoil compaction, which is almost reversible by tillage, subsoil compaction persists over the long term, because its recovery takes decades (Alakukku et al., 2003; Berisso et al., 2012).

The risk of anthropogenic subsoil compaction depends on many factors, for example soil type, texture, structure stability, pre-loading history (pre-compression stress), and the moisture content or matric potential at the time of stress application (Horn & Fleige, 2003, 2009; Jones, Spoor, & Thomasson, 2003). More than a third of European subsoils are classified as "high" to "very high susceptible" to compaction (Jones et al., 2003). Also 10% of German arable soils are estimated to be susceptible to compaction due to unfavourable structural conditions corresponding to a low internal stability against mechanical stresses indicated by the pre-compression stress value (Lebert, 2010). This proportion increased to 68%, when the soils are at a moisture level reaching field capacity (matric potential of -6 kPa). At matric potentials of -6 kPa and higher (wetter), soils are very susceptible to soil compaction (Batey, 2009). For soils in North Germany (Schleswig-Holstein), those derived from naturally compacted glacial till likely possess a high bearing capacity under lower moisture levels (at least below field capacity) (Zink et al., 2010), but the risk of harmful subsoil compaction is high, because even the smallest alteration in soil functions leads to harmful soil conditions, especially under wet conditions. Gleysols and Fluvisols derived from marsh sediments with low bulk density are also highly sensitive to compaction (Horn & Fleige, 2009). The verification of "harmful soil alterations" according to the German Federal Soil Protection Law (BBodSchG, 1998) requires the differentiation between the natural and the anthropogenic percentage of soil compaction. This also helps to secure evidence of potentially harmful soil degradation processes, like at cable construction sites (Zink, Fleige, Gebhardt, & Horn, 2013).

This paper presents (a) the subsoil compaction status of 7 soil types in the federal state of Schleswig-Holstein (North Germany) based on the physical soil parameters of a soil profile database provided by the State Agency for Agriculture, Environment and Rural Areas of Schleswig-Holstein (LLUR) and (b) the anthropogenic share of a potentially harmful subsoil compaction for selected soil types. The parameters used were air capacity (AC), saturated hydraulic conductivity (K_s), and (effective) bulk density (ρ_{Beff}). To determine whether the compaction can be valued as potentially harmful, approved critical threshold values were used (Horn & Fleige, 2009; UBA, 2004).

2 | MATERIAL AND METHODS

2.1 | Database

The data used had been collected and analysed over the last 45 years during various research programmes in Schleswig-Holstein by LLUR, as well as its predecessor agencies. Cooperating institutions also contributed data, including the soil science laboratory at Kiel University. Undisturbed and disturbed soil samples were taken depth-wise or horizon-specific down to at least the 60 cm depth across the four geological regions of Schleswig-Holstein under different land use (among them arable, grassland, forest use) (Figure 1). The four regions were the Weichselian glacial region in the east (younger moraine area, 6,740 km[2]), the sandy outwash region called "Lower Geest" (2,010 km[2]), the Saalian glacial region (older moraine area or "Higher Geest", 3,766 km[2]) in the centre, and the marshland with alluvial deposits in the west (2,854 km[2]).

The sampling started in the 1970s for the national soil type mapping "Bodenkarte 1:25" ("BK25") in the scale 1:25,000. The forest sites were sampled more intensely by the forest soil condition survey ("Bodenzustandserhebung l" (BZE I), 1990 and 2006–2007). Additionally, sites were sampled in the long-term soil monitoring programme ("Bodenkundliche Dauerbeobachtungsflächen" ("BDF sites"), 1989–1992). Later on (from 2007), data were continuously collected for the overview map of soil types in Schleswig-Holstein at the scale 1:50,000 ("Bodenübersichtskarte 1:50", "BÜK 1:50"). Whereas the majority of marshland samplings was completed in the mid-1990s, samplings in the other geological regions were continuously conducted from the mid-1970s until 2015.
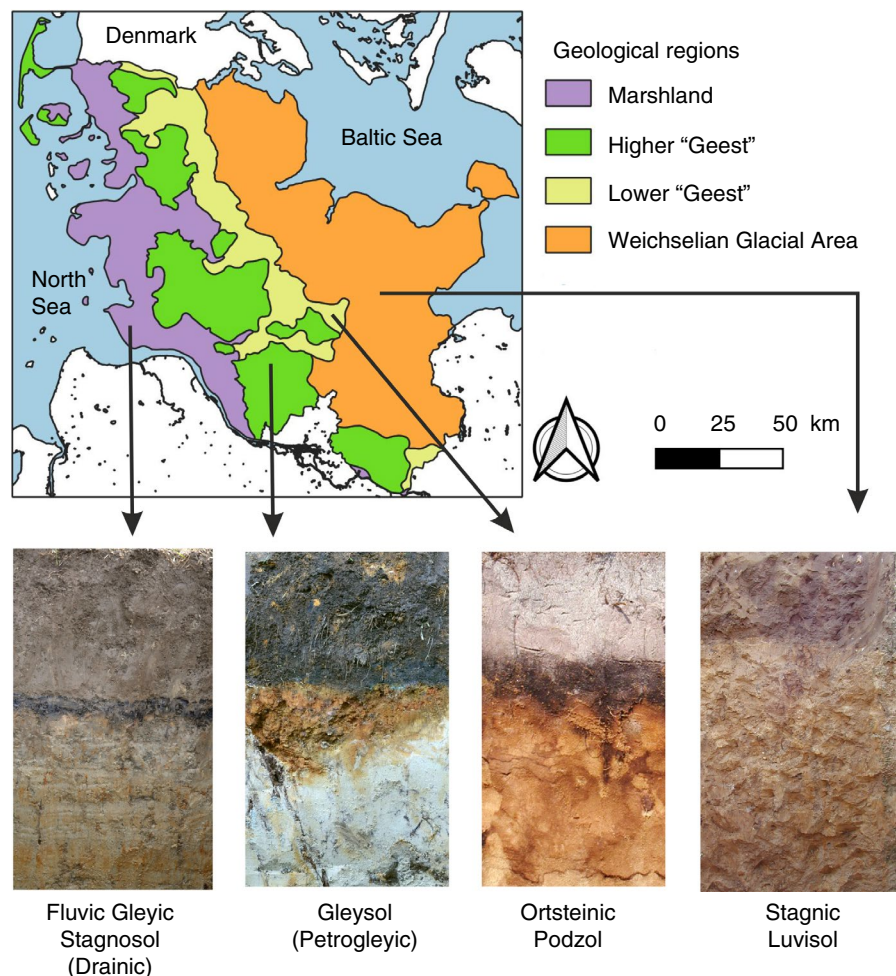
FIGURE 1 Geological regions of the federal state Schleswig-Holstein (North Germany) and their associated soil types with naturally compacted soil horizons (an example is shown). Map basis from BKG (2010), edited

Fluvic Gleyic Stagnosol (Drainic)

Gleysol (Petrogleyic)

Ortsteinic Podzol
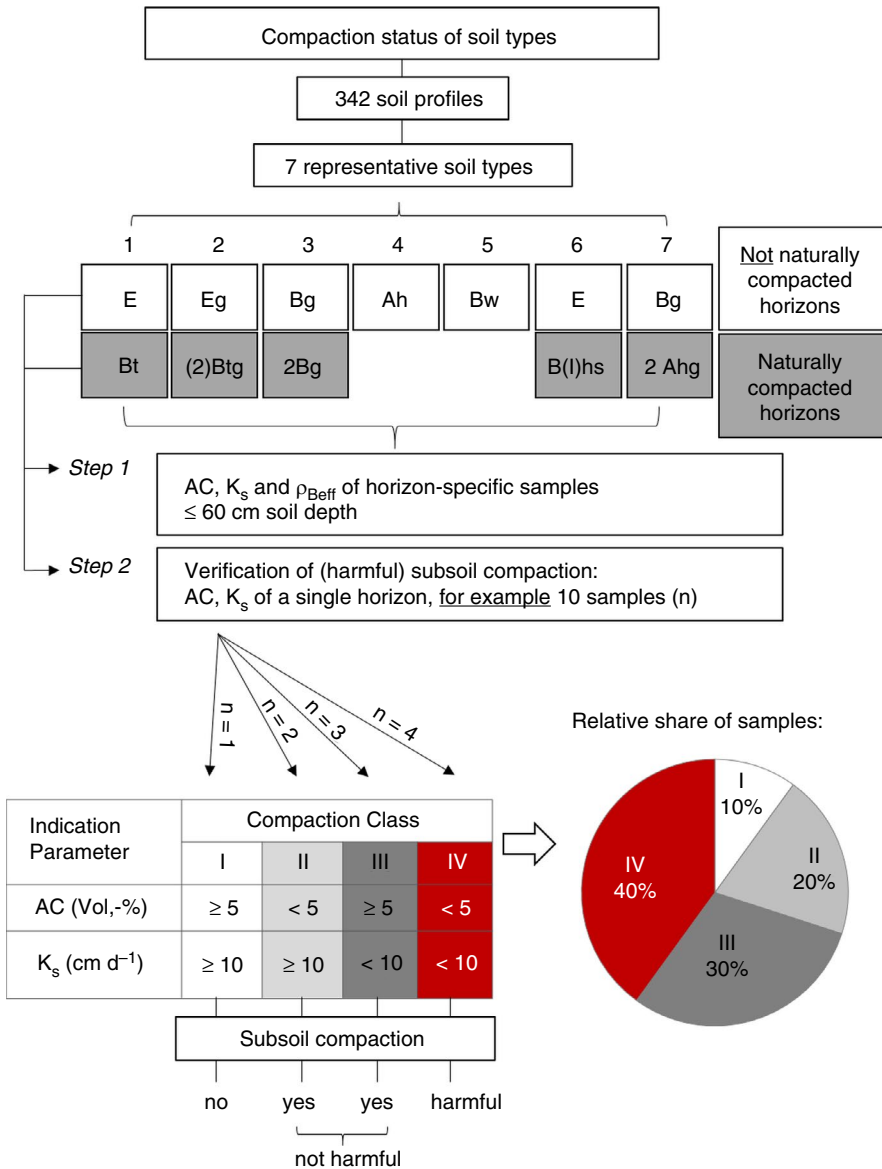
Stagnic Luvisol

FIGURE 2 Methodical approach to evaluate the horizon-specific subsoil compaction status (≤ 60 cm depth) of 7 representative soil types in Schleswig-Holstein: 1 = Luvisol, 2 = Stagnic Luvisol, 3 = Stagnosol, 4 = Anthrosol, 5 = Brunic Arenosol, 6 = (Gleyic) Podzol, 7 = Fluvic Gleyic Stagnosol. Critical values (AC < 5, K_s < 10 cm day^{-1}) indicate a potentially harmful subsoil compaction status (Horn & Fleige, 2009)

Bulk density (ρ_B), effective bulk density (ρ_{Beff}), saturated hydraulic conductivity (K_s) and air capacity (AC) (air-filled pore volume at -6 kPa) were determined on undisturbed soil samples (100 cm^3), while grain size distribution (among others) was analysed on disturbed samples. ρ_B is defined by the oven-dried soil mass (105°C) per sample volume (100 cm^3), whereas the ρ_{Beff} is a simple soil description parameter for structure analysis in the field according to the German soil classification system (Ad-hoc-AG Boden, 2005). It also considers the compaction effect of soil texture, because, especially in fine-textured soils, root penetration could be limited by a high packing density (FAO, 2006), which could alter microbial processes affecting crop production (Beylich, Oberholzer, Schrader, Höper, & Wilke, 2010). ρ_{Beff} is calculated as follows (Ad-hoc-AG Boden, 2005; FAO, 2006):

$$\rho_{Beff} = \rho_B \left[\text{g cm}^{-3} \right] + 0.009 \times \text{Clay Content [\%]} \quad (1)$$

The test method for analysing the K_s was almost identical throughout the decades (falling head method according to Hartge, 1966 and Kretzschmar, 1996). AC was derived from the water-retention functions and corresponded to the amount of wide coarse pores > 50 μm representing the soil water content at field capacity at -6 kPa according to Ad-hoc-AG Boden (2005). The methodical details are given in Hartge and Horn (2016). $\rho_{B(eff)}$, K_s and AC were classified according to Ad-hoc-AG Boden (2005) and Horn and Fleige (2003).

2.2 | Data analysis

The data analysis was performed for subsoil horizons above the 60 cm depth under grassland and arable use (at the time of sampling) of 7 representative soil types, which cover 60% of the total land surface of Schleswig-Holstein. An overview of the spatial and relative distribution of soil types in the four

FIGURE 3 Methodical approach to distinguish between natural and potentially anthropogenic subsoil compaction from single soil profiles of different soil types with a sequence of horizons without (horizon 1, like E, Eg and Bg horizons) above ones with natural subsoil compaction (horizon 2, like Bt, (2)Btg, 2Bg and 2Ahg horizons)
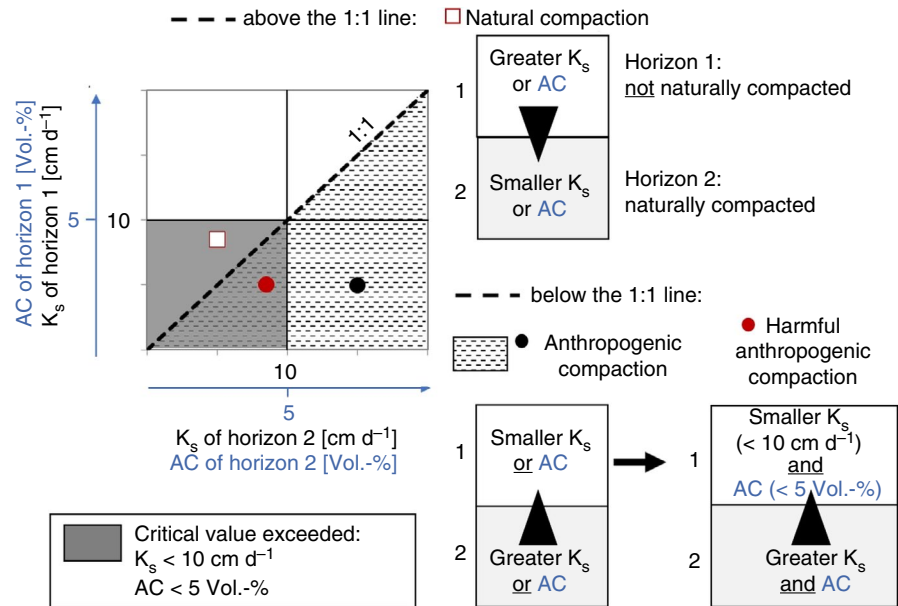
geological regions is given in Mordhorst et al. (2018). This amounted to 342 soil profiles, which were extracted from the data base (that contained > 900 soil profiles). They were evaluated with respect to the soil physical parameters, which were bulk density and effective bulk density (ρ_B and ρ_{Beff}), air capacity (AC) and saturated hydraulic conductivity (K_s) to identify the compaction status in the subsoil (Figure 2: step 1).

Soil types with naturally compacted origins (pedogenically or geogenically induced) were selected, as well as the major soil types of the four geological regions (see Figures 1 and 2). The Weichselian glacial region is represented by Luvisols, Stagnic Luvisols, Stagnosols and Anthrosols derived from colluvic material (topsoil material which has moved downhill). Because soil erosion is a widespread phenomenon in this hilly moraine landscape, colluvic horizons are common, which is reflected by a share of 16% with each soil type according to the soil overview map for Schleswig-Holstein at the scale 1:250,000 (BÜK S.-H. 250), and > 20% in certain geomorphological units (Richter, Fleige, Blume, & Horn, 2007). The flat sandy outwash area, "Lower Geest", is characterized by (Gleyic) Podzols and Brunic Arenosols. The hilly moraine area, "Higher Geest", is characterized by Stagnosols and Gleyic Podzols, and the marshland has Fluvic Gleyic Stagnosols (Clayic, Drainic). Stagnosols from the moraine area are of geogenic origin caused by stratification (e.g. sandy above loamy material) or have resulted from pedogenic processes (clay migration), whereas Fluvic Gleyic Stagnosols are formed by sedimentation processes due to regression and transgression phases of the seawater level. The latter are characterized by buried (fossil), compacted topsoil horizons inducing stagnic properties (2 Ahg horizon, called "Dwog").

2.3 | Indication of potentially harmful subsoil compaction

The extent of subsoil compaction was evaluated based on critical thresholds for AC: 5 Vol.-% and K_s: 10 cm day^{-1} relating to crop production (Horn & Fleige, 2009; Seehusen et al., 2014; UBA, 2004; Zink, Fleige, & Horn, 2011). The verification of subsoil compaction based on the four compaction classes I–IV (step 2, Figure 2):

- Class l: AC and K_s <u>do not</u> exceed (are greater than) the critical threshold values
- Classes ll and lll: AC <u>or</u> K_s exceed (is smaller than) the critical threshold value
- Class lV: AC <u>and</u> K_s exceed (are smaller than) the critical threshold values (potentially harmful subsoil compaction)

AC and K_s are considered as parameters with high indication for subsoil compaction related to soil structure functionality (Horn & Fleige, 2009). In contrast, compaction-sensitive parameters, such as bulk density and effective bulk density (ρ_B or ρ_{Beff}), are considered to give a poor indication, because they describe only volume changes but do not quantify the potentially negative impacts on pore functions. However, ρ_{Beff} values > 1.7 g cm^{-3} imply harmful changes of the soil with respect to negative effects on microbial processes affecting crop production (Beylich et al., 2010). In line with statutory specified tests and action values by the German Federal Soil Protection Law (BBodSchG, 1998), which differentiate between the suspicion and the existence of harmful soil function changes, Horn and Fleige (2009) defined the critical threshold values for AC (5 Vol.-%) and K_s (10 cm day^{-1}) as action values,

while the critical threshold value for ρ_{Beff} (1.7 g cm^{-3}) is only suggested as test value.

2.3.1 | Anthropogenic proportion of subsoil compaction

The derived compaction status (see Figure 2) includes both natural and potentially anthropogenic compactions in the subsoil. In a next step, the anthropogenic proportion of the compaction was quantified according to Figure 3, and potentially harmful subsoil compactions were evaluated. Therefore, K_s and AC values were classified for single soil profiles with pedogenic or geogenic compacted horizons, which is true for (Stagnic) Luvisols and Stagnosols. If K_s and AC values of the soil overlying horizon (horizon 1), for example albic material, are smaller than those in the naturally compacted one (horizon 2), which would be contrary to the pedogenesis of the soil type, an anthropogenic compaction share can be verified for the soil profile (corresponded to values below the 1:1 line in Figure 3). For this profile-specific evaluation method, subsoil horizons below the 60 cm depth were included to increase the number of soil profiles with a sequence of horizons without (horizon 1) above ones with natural subsoil

compaction (horizon 2). Otherwise, the quantity of evaluated soil profiles was restricted, because in some cases the naturally compacted soil horizon began beneath the 60 cm depth.

3 | RESULTS AND DISCUSSION

3.1 | Natural soil compaction

The total area of soil types with naturally compacted horizons (based on the soil overview map "BÜK S.-H. 250", only dominant and associated soils were considered) was 42% in Schleswig-Holstein (Table 1). Soil types, (Stagnic-)Luvisols and Stagnosols (Weichselian glacial region and "Higher Geest") occupied the largest area, followed by the compacted or cemented subsoil horizons of the (Gleyic-)Podzols of the "Geest", as well as the clayey horizons ("Knick") or humus-rich buried A horizons ("Dwog") of the Fluvic Gleyic Stagnosols in the old marshlands.

These soil types/horizons were developed from different parent material (defined as C horizons). Consequently, their natural bulk density (ρ_B), AC and K_s can vary widely depending on the geogenesis and sedimentation processes (Figure 4). Marine sediments, which are the dominant parent material of

TABLE 1 Absolute and relative areal proportion of soil types with natural compaction based on the soil overview map 1:250,000 (BÜK S.-H. 250) in Schleswig-Holstein (total area = 15,370 km^2)

Soil type (FAO, 2015)	Parent material	Dominant geological region	Abs. area [km^2]	Rel. area [%]
Stagnosol	(Glacial sand above) glacial loam	Weichselian glacial region, "Higher Geest"	1,814	12
Stagnic Luvisol	Glacial loam	Weichselian glacial region	1,552	10
Gleyic Podzol	Aeolian, glacifluvial or glacial sand	"Higher" and "Lower Geest"	1,214	8
Fluvic Gleyic Stagnosol (Clayic, Drainic)	Marine sediment	Marshland	753	5
Haplic Luvisol	Glacial loam	Weichselian glacial region	646	4
Podzol	Aeolian, glacifluvial or glacial sand	"Higher" and "Lower Geest"	354	2
Stagnic Podzol	Aeolian, glacifluvial or glacial sand above glacial loam	"Higher Geest"	200	1
Gleysol (Petrogleyic, with "bog iron")[a]	Glacifluvial or glacial sand	"Higher" and "Lower Geest"	46	< 0.3
Sum			6,579	42

[a]Holthusen, Neugebauer, Burbaum, Fleige, and Horn (2015).
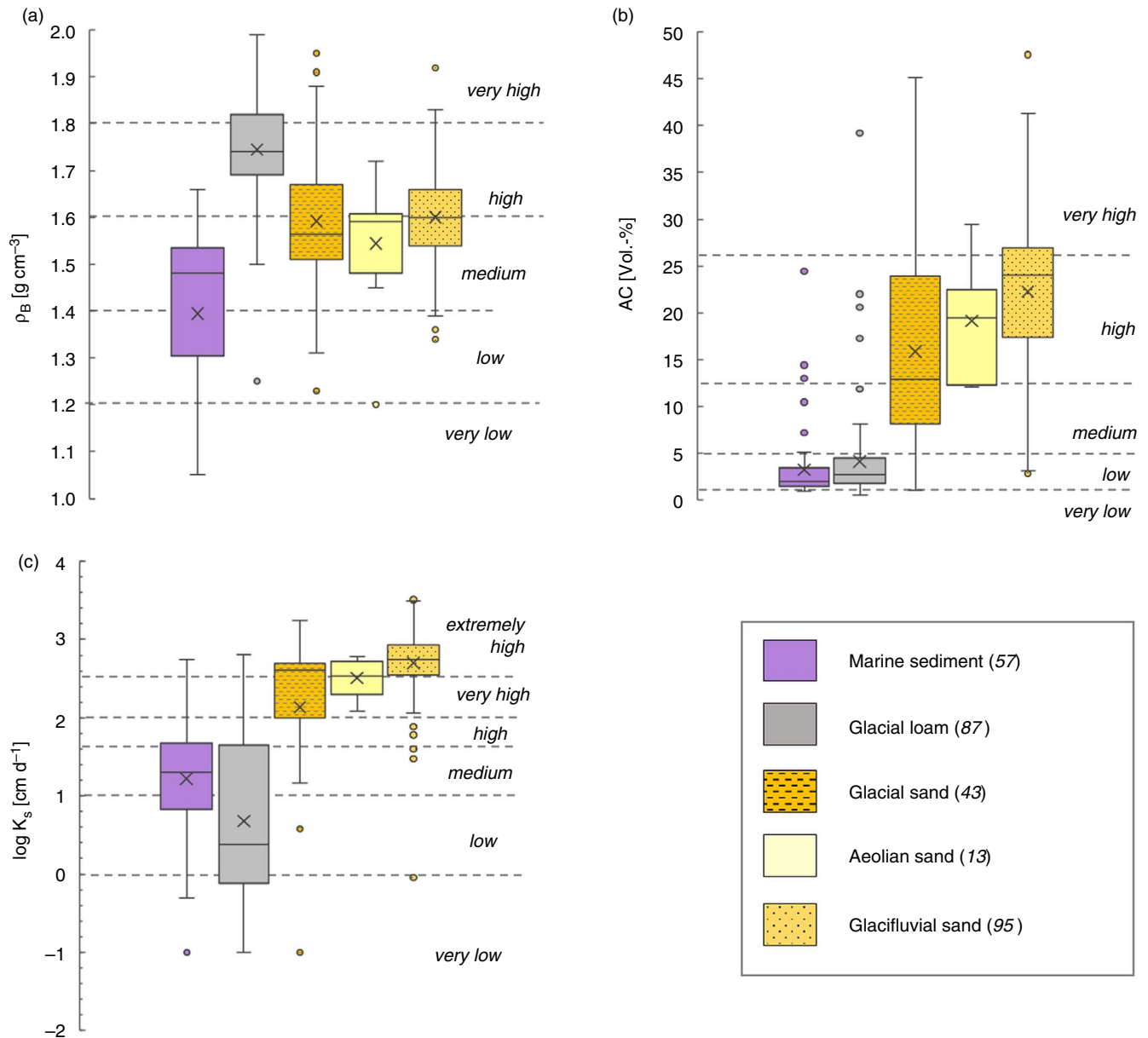
FIGURE 4 Physical properties of C(r) horizons derived from different parent material: (a) Bulk density (ρ_B), (b) air capacity (AC), (c) saturated hydraulic conductivity (K_s). Numbers in brackets correspond to number of replications (LLUR database)

C horizons in the coastal marshland areas, showed "low" to "medium" ρ_B, "medium" K_s and "low" AC values. This material is affected by sedimentation processes, which involve a wide range of clay content. However, C horizons derived from glacial sand or loam are naturally compacted, because of their mechanical compression by the ice load during the ice age periods. For this reason, a high degree of natural compaction occurs in soil types like Calcaric Cambisols or Calcaric Regosols (occurring in hilltop or upper slope areas resulting from pronounced erosion), because they are formed from non-weathered glacial till. In comparison with Luvisols, losses in crop yield on these soils can be expected (Goeck et al., 1988).

C horizons from glacial loam were characterized by "high" ρ_B with "low" AC and K_s (20.0 ± 7.9% clay), while, as expected, those from glacial sand (< 10% clay) were less negatively affected by the compression and showed "medium" (to "high") ρ_B with "very high" K_s and "high" AC due to its coarser texture (average sand proportion of 86%) and its large volume of primary coarse pores (Hartge & Horn, 2016).

Glaciofluvial and aeolian sands as parent material are not considered as naturally compacted material, but they show "medium" to "high" ρ_B and a higher AC ("high") and "very high" to "extremely high" K_s compared to the glacial sand. Soil types derived from the overlay of different parent materials with contrasting physical properties (Figure 4) were

Stagnosols in the "Higher Geest", developed from aeolian sand or glacial sand above (saalean) glacial loam.

3.2 | Compaction status of soil types

The compaction status is presented for subsoil horizons of the 7 representative soil types of Schleswig-Holstein by the parameters ρ_{Beff} (Table 2) as well as AC and K_s (Figures 5 and 6). Values differed across the horizons, and their critical limits were exceeded to various extents, which means AC and K_s values are smaller than 5 Vol.-% and 10 cm day^{-1}, respectively. Largest mean AC (15 Vol.-%) and K_s values (> 100 cm day^{-1}) were found in the Bw horizons of Brunic Arenosols and in the E and Bhs horizons of Podzols (Figure 5). Their mean AC, K_s and ρ_{Beff} were far better than the corresponding critical thresholds. Additionally, more than 63% of the horizons did not indicate any subsoil compaction, because neither AC nor K_s values exceeded the critical values (Class I) (Figure 6). The same was true for Anthrosols, which consisted of loosely deposited colluvic material (corresponding to a "medium" ρ_{Beff}, Table 2). The colluvic horizon occurred in a large proportion of samples in Class I (61%), but, at the same time, the share of samples in Class IV (18%) is larger compared with that in Brunic Arensols and (Gleyic) Podzols (4%–13%).

This proportion was comparable to E(g) horizons from (Stagnic) Luvisols (18%–21%) and was greatest (ca. 60%) for the clay-rich (18%–40% clay content) Bt(g) horizons of (Stagnic) Luvisols and the "Dwog" horizons of Fluvic Gleyic Stagnosols. Although this large proportion was limited to the deeper, predominately naturally compacted horizons, the

overlying stagnic Bg horizons of Stagnosols also indicated an increased proportion (39%–50%) of samples in Class IV, which indicated a potentially harmful subsoil compaction (Figure 6).

The results highlight that soil types derived from naturally compacted glacial loam with high bearing capacity (Zink et al., 2010) are still vulnerable to further anthropogenic compaction from agricultural use, because even small alterations in soil functions lead to harmful soil conditions for crop production (AC < 5 Vol.-%, K_s < 10 cm day^{-1}). Compared with Eutric or Calcaric Fluvic Gleysols in the younger marshlands, which are highly sensitive to compaction due to their small bulk density (Horn & Fleige, 2009), the Fluvic Gleyic Stagnosols in the older marshlands are already characterized by a high natural compaction status (due to sedimentation) with low hydraulic conductivity and aeration level (Müller, 1994).

The results also show a similar risk of harmful subsoil compaction by further external stress applications, especially in undrained conditions (high groundwater level). Under moist conditions (matric potential > −6 kPa), the oxygen diffusion rate is often limited by the remaining low amount of air-filled pores even for soils with adequate AC (≥ 5 Vol.-%). Consequently, Horn and Fleige (2009) recommended a higher critical value of 8 Vol.-% for soils with stagnic or gleyic properties (hydromorphic soils) to ensure sufficient oxygen availability.

Ninety per cent of the possibly naturally compacted B(l) hs of (Gleyic) Podzols were classified in Class I, while only 4% of samples indicated a potentially harmful subsoil compaction status (Figure 6). This suggests that cementation, or rather the resultant formation of an "ortsteinic" horizon, is unlikely or not often represented in these horizons. Lipiec,

TABLE 2 Mean soil physical properties of evaluated subsoil horizons of representative soil types of Schleswig-Holstein

Soil type according to WRB (FAO, 2015)	Rel. Area [%]	Horizon (FAO, 2006)	n	Clay content Mean [%]	SEM [%]	ρ_B Mean [g cm^{-3}]	SEM [g cm^{-3}]	ρ_{Beff} Mean [g cm^{-3}]	SEM [g cm^{-3}]	> 1.7 [%]
Luvisols	4	E	20	12.82	1.25	1.67	0.02	1.78	0.03	75
		Btg	29	18.87	1.06	1.74	0.02	1.91	0.02	100
Stagnic Luvisols	10	Eg	28	11.40	1.12	1.68	0.02	1.79	0.02	75
		(2)Btg	40	31.30	1.83	1.71	0.01	1.99	0.02	100
Stagnosols	12	Bg	74	13.05	0.88	1.68	0.01	1.80	0.01	78
		2Bg	48	25.02	2.14	1.65	0.03	1.88	0.02	94
Anthrosols	9	Ah (subsoil)	38	9.2	1.43	1.46	0.02	1.55	0.02	5
Brunic Arenosols	12	Bw	118	4.76	0.27	1.57	0.01	1.62	0.01	18
(Gleyic) Podzols	10	E	8	4.83	0.70	1.53	0.04	1.56	0.04	13
		B(l)hs	170	3.87	0.19	1.51	0.01	1.55	0.01	7
Fluvic Stagnosol (Clayic, Drainic)	3	Bg	35	33.88	1.69	1.44	0.02	1.74	0.02	80
		2Ahg	53	40.26	1.42	1.39	0.01	1.75	0.01	77
Sum $\sum$	60		661							

Abbreviations: ρ_B, Bulk density; ρ_{Beff}, Effective bulk density with its relative proportion of values exceeding the critical threshold of 1.7 g cm^{-3}; Mean, arithmetic mean; n, number of samples; SEM, standard error of the mean.

Świeboda, Chodorowski, Turski, and Hajnos (2018) determined a volumetric decrease of large pores, while the volume of small pores increased, in the "ortstein" compared to the overlying E horizons. However, these changes in pore size distribution are not reflected by the greater K_s and AC of the B(l)hs compared to the E horizons. While the investigations of Lipiec et al. (2018) were conducted on aggregates 6–8 mm in size, sampling of undisturbed soil samples of higher volume (100 cm^3) from cemented horizons is very difficult due to the strongly impeded layer, which suggests that the sampling of B(l)hs horizons was limited to less cemented ones, and this explains their high level in pore functionality (Figures 5 and 6). Although coarse sandy soils might contain adequate K_s and AC properties even after stress application, compaction could result in a high packing density restricted for root penetration in the subsoil (Batey, 2009). For these soil types, Horn and Fleige (2009) discussed whether other soil physical threshold values, like the ρ_{Beff} with a threshold value of > 1.7 g cm^{-3}, should be considered. The investigated sandy soils had mean ρ_{Beff} values between 1.55–1.62 g cm^{-3}, which ranged from "low" to "medium" (Table 2). The threshold value was exceeded in the Brunic horizons of Arenosols in every fifth profile (18 % > 1.7 g cm^{-3}), while the smallest ρ_{Beff} were found in Anthrosols and (Gleyic) Podzols and only 5%–13% of the samples exceed the critical threshold.

In contrast, mean ρ_{Beff} (ranging from 1.74 to 1.80 g cm^{-3}) of the not naturally compacted horizons of Stagnosols and (Stagnic) Luvisols was classified as "medium" and "high", more than 75% of samples exceeded the critical value of 1.7 g cm^{-3} (Table 2).

3.2.1 | Potential share of anthropogenic soil compaction

The compaction status alone does not reveal the anthropogenic share of the compaction. Zink et al. (2011) verified a harmful subsoil compaction of anthropogenic origin by comparing the soil state before (initial state) and after machinery wheel passes. According to their concept, harmful alterations could be defined by a degradation increase of 25% in Class IV. However, in this paper, the initial state is not known, and thus, the anthropogenic impact on soil compaction was derived for each specific soil type by consideration of geogenic/pedogenic processes. As an example, consider the (Stagnic) Luvisols and Stagnosols (Figure 7) as follows: When K_s and AC of the naturally compacted horizon (horizon 2 corresponds to Bt, (2) Btg, 2Bg or 2Ahg) are directly compared with its overlying, not naturally compacted one (horizon 1 corresponds to E(g) or Bg) within the same soil profile (pair of values), 21%–38%
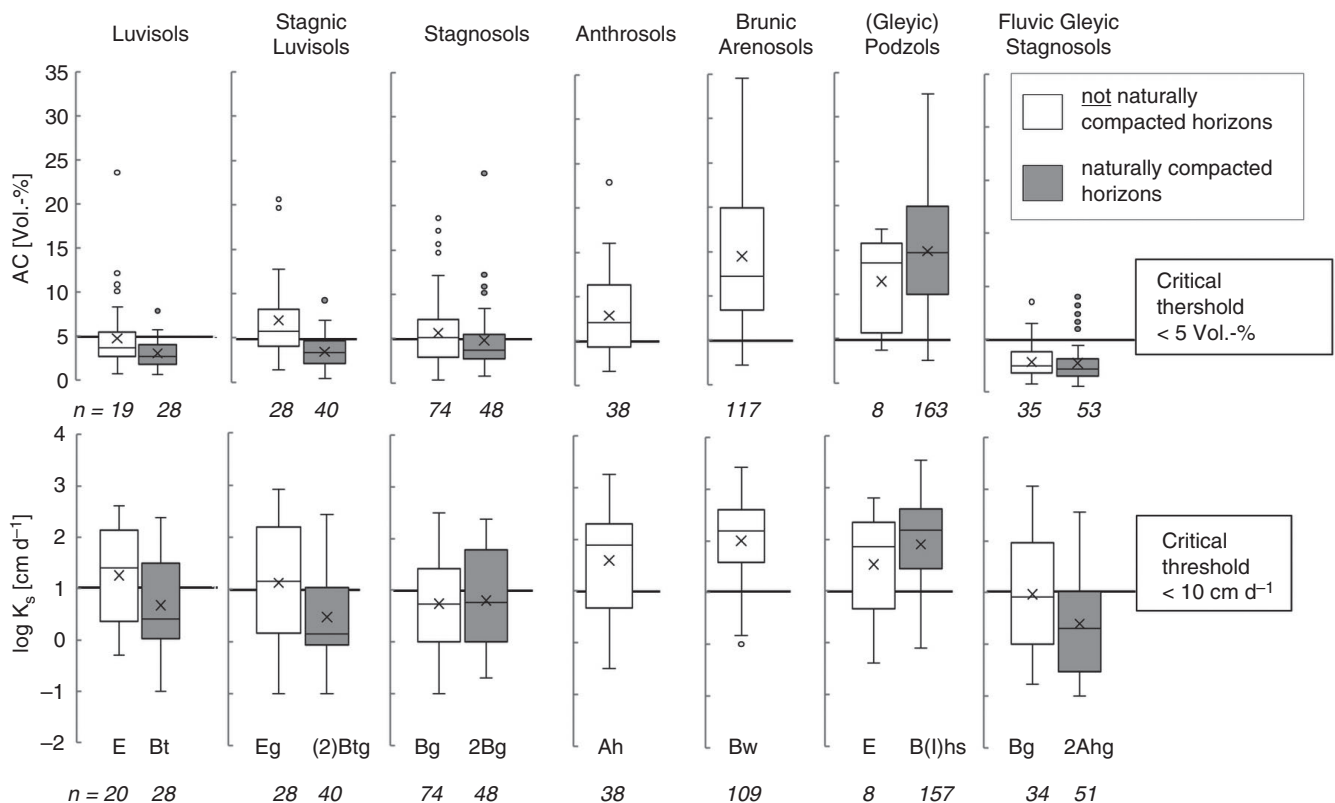
FIGURE 5 Air capacity (AC) and saturated hydraulic conductivity (K_s) of selected subsoil horizons of representative soil types in Schleswig-Holstein (≤60 cm depth). n = number of sampled horizons. Critical values indicate a potentially harmful subsoil compaction status (Horn & Fleige, 2009)
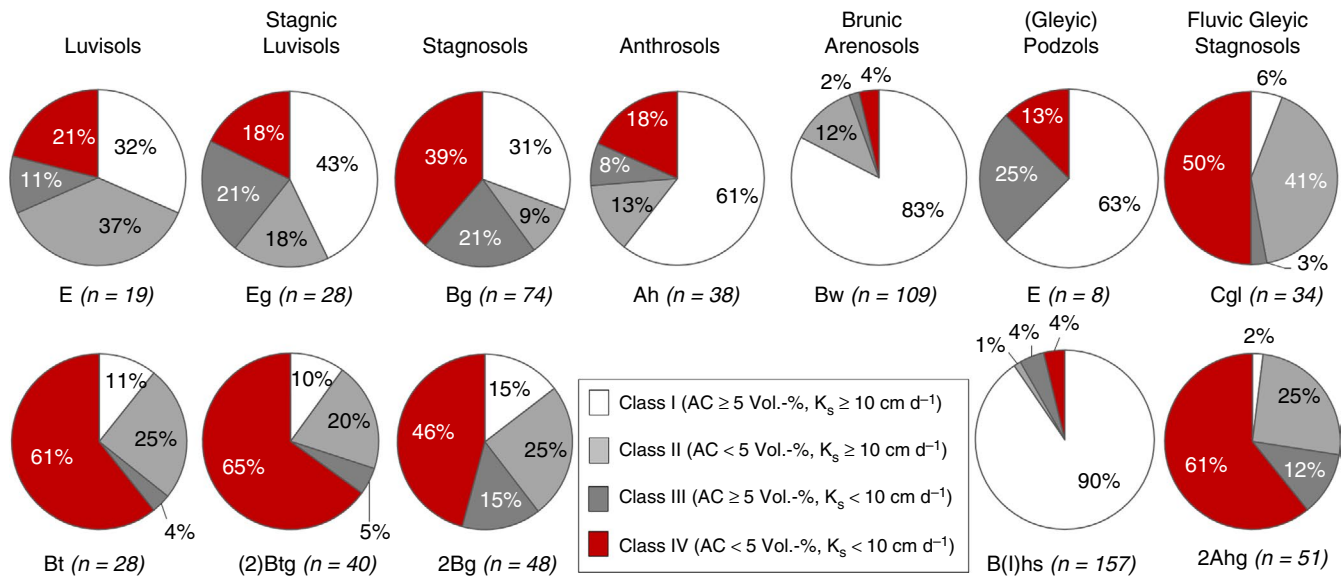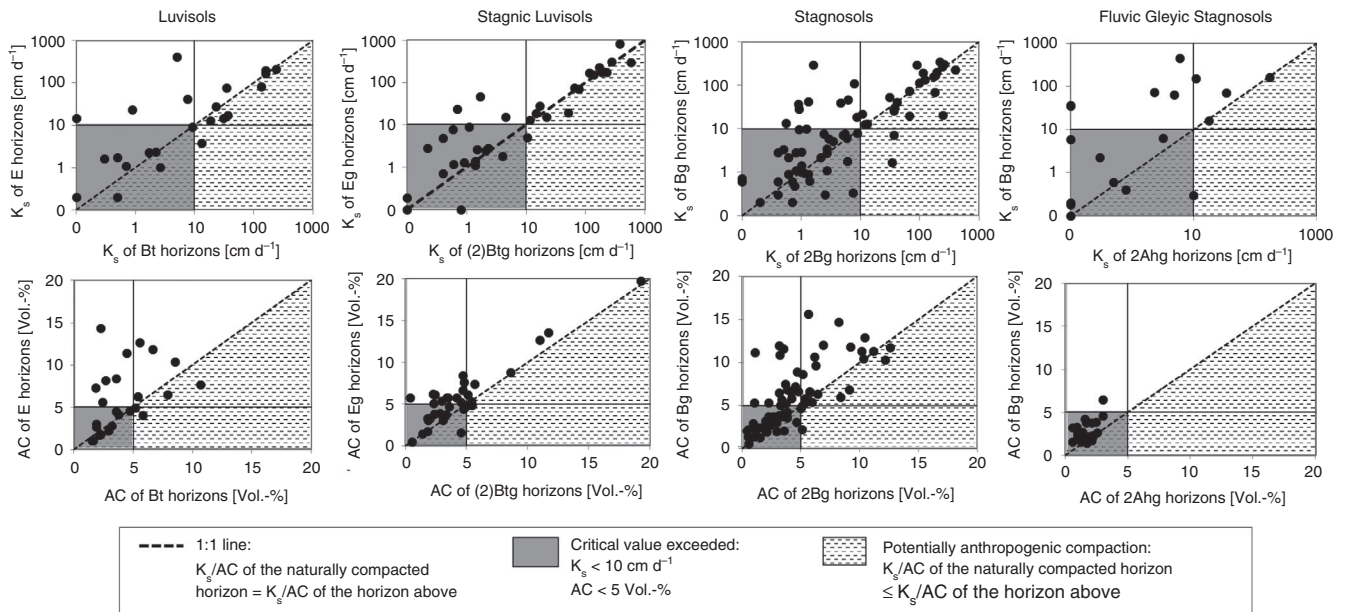
FIGURE 6 Evaluation of the soil compaction status of selected subsoil horizons of representative soil types in Schleswig-Holstein based on the subsoil compaction classes I–IV according to Zink et al. (2011)

(Table 3) of the overlying horizons show a smaller K_s and 10% – 46% (Table 3) a smaller AC compared to the naturally compacted horizon underneath. For soils from the moraine areas (Weichselian glacial region and "Higher Geest"), more than a third of the K_s and at least a quarter of the AC values (Table 3) were found to be smaller in the overlying E and stagnic (Eg or Bg), but primary water conducting horizons, than in the water confining 2Bg and (2)Bt(g)-horizons, which contradicts the pedogenesis of these soil types.

If this profile-specific share exceeded the critical threshold values for both K_s and AC (corresponding to Compaction Class IV) in the overlying horizon, the subsoil compaction can be additionally defined as potentially anthropogenic-induced harmful subsoil compaction. This is included in Table 3, which summarizes the relative share of the potentially anthropogenic subsoil compaction for the soil types. Only the horizons that are not naturally compacted with their relative share of samples in Class IV (derived from Figure 6) together with their anthropogenic share (derived from Figure 7) are shown. A potentially anthropogenic, harmful subsoil compaction can be assigned to at least 6%–10% of the soil profiles. The proportion increases from Stagnic Luvisols (6%) to Luvisols and Stagnosols (both 8%) to Fluvic Gleyic Stagnosols (10%). The latter are most clayey (average of 34% clay in the Bg horizon) and possess an already naturally high compaction status, which could be explained by their finer soil texture (< 100 μm) and the recurrent horizontally fine layering due to sedimentation and dispersion processes (Müller, 1955, 1994). Because of their compacted horizons with stagnic properties, they are not usable for arable land and, consequently, are mostly under grassland use (Janetzko & Fleige, 2010). In both horizons, 95% of AC values exceeded the critical value, which impedes the determination

of their anthropogenic share (Figure 7). Although it is not directly provable, a potentially high share of anthropogenic compaction can be also assumed for Anthrosols. Despite the loose deposition of the colluvic material, 18% of them are classified in Class IV, potentially due to anthropogenic impacts. Their high sensitivity to mechanical deformation has already been shown by soil mechanical investigations, including one on an arable Stagnic Anthrosol derived from colluvic material (Weichselian glacial region) (Horn & Fleige, 2009; Mordhorst, 2009). Compared to a naturally stable Stagnic Luvisol derived from glacial till (same site), soil deformation processes and negative alterations in soil functions are only evident in the Ah subsoil horizon, because of the small values of density and structural stability.

The differentiation between natural and anthropogenic compaction is important for determining "harmful soil alterations", according to the German Federal Soil Protection Law (BBodSchG, 1998). If the action value is defined by the critical threshold value of AC and K_s (Horn & Fleige, 2009), the estimated share of anthropogenic compaction is even greater, because anthropogenic-induced compaction has occurred without the need for the AC/ K_s value of the overlying horizons to be smaller than that for the naturally compacted horizons. The anthropogenic share of the marshland soils might be also underestimated, because the samplings were conducted in the mid- 1990s. Consequently, potential compaction processes resulting from increasing intensification and mechanization of agricultural practices are not reflected in the data set. Thus, the presented subsoil compaction status corresponds only to a minimum compaction level. The current degree of subsoil compaction is expected to be greater, if further compaction processes are also be included, which have occurred after that sampling, because of agricultural use during the recent past. To estimate

FIGURE 7 Evaluation of the potentially anthropogenic subsoil compaction from different soil types with a sequence of horizons without (like E(g) and Bg) above ones with natural subsoil compaction (like Bt(g), (2)Bg and 2Ahg horizons). Values below the 1:1 line correspond to a potentially anthropogenic subsoil compaction, while values in the grey box exceed the critical values of K_s and AC, respectively, indicating a harmful soil compaction

TABLE 3 Potentially harmful subsoil compaction of representative soil types in Schleswig-Holstein indicated by the relative proportion of samples in Class IV ($K_s < 10$ cm day^{-1}, AC < 5 Vol.-% according to Horn & Fleige, 2009) and their derived relative anthropogenic share from the profile-specific evaluation

Soil type according to WRB (FAO, 2015)	Horizon (FAO, 2006)	n	Potentially harmful subsoil compaction (% in Class IV)	Anthropogenic share of subsoil compaction in %		
				AC	K_s	AC + K_s in Class IV
Fluvic Gleyic Stagnosol (Clayic, Drainic)	Bg	34	50	10	21	10
Stagnosols	Bg	74	39	25	38	8
Luvisols	E	19	21	46	38	8
Stagnic Luvisols	Eg	28	18	25	34	6
Anthrosols	Ah	38	18	-		
(Gleyic) Podzols	E	8	13	-		
Brunic Arenosols	Bw	109	4	-		

the present compaction status, a renewed sampling of representative soil profiles is required, especially in the marshland and the Weichselian glacial regions.

Prevention of a further increase in harmful subsoil compaction is necessary to ensure adequate crop productivity and food security in the future, when drier conditions may prevail (Colombi, Torres, Walter, & Keller, 2018; Hartmann et al., 2012). Hence, in the future, when more intensive drying phases but a greater frequency of heavy precipitation events result from climate change (IPCC, 2018), the persistence of heavy compaction zones acting as rooting barriers (such as in the plough pan) would not only constrain necessary water

and nutrient uptake from deeper soil depths but also prevent greater rain water infiltration to depth. On a larger scale, Rogger et al. (2017) and Alaoui et al. (2018) related such effects of soil compaction to landscape flooding together with massive off-site soil erosion.

4 | CONCLUSIONS

The verification of "harmful soil alteration", according to the German Federal Soil Protection Law, requires the differentiation between natural (pedogenic/geogenic) and

anthropogenic compaction by agricultural or forestry use. Therefore, the calculated subsoil compaction status (derived by the soil indicator parameters, AC and K_s) strongly depends on the soil type and the horizon-dependent internal soil stability. While the predominating naturally compacting horizons of the mostly loamy (Stagnic) Luvisols and clayey Fluvic Gleyic Stagnosols indicate the largest, potentially harmful, subsoil compaction (max. 61% in Class IV), the subsoil horizons of sandy (Gleyic) Podzols and Brunic Arenosols are rarely affected by harmful subsoil compaction ($\leq$ 13% in Class IV). In these latter soils, less than 1/5 of ρ_{Beff} values exceed the critical limit of 1.7 g cm^{-3}. The share of harmful subsoil compaction increases for Anthrosols (18% in Class IV), supposedly from anthropogenic soil compaction. Evidence of an anthropogenic share of at least 6%–10% could be verified for (Stagnic) Luvisols and (Fluvic Gleyic) Stagnosols, which was based on a simple approach that takes into account horizon-specific pedogenic/geogenic processes within single soil profiles to identify the anthropogenic share of harmful subsoil alterations.

However, the current compaction status is expected to be greater, because a majority of samplings took place before 1990. These data can be used, therefore, as a reference (status quo) to quantify the actual status and the corresponding changes.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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REFERENCES
Ad-hoc-AG Boden (2005). *Bodenkundliche Kartieranleitung* (5 Auflage). Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

Alakukku, L., Weisskopf, P., Chamen, W. C. T., Tijink, F. G. J., van der Linden, J. P., Pires, S., … Spoor, G. (2003). Prevention strategies for field traffic-induced subsoil compaction: A review: Part 1. *Machine/soil Interactions. Soil & Tillage Research*, *73*(1–2), 145–160. https://doi.org/10.1016/S0167-1987(03)00107-7

Alaoui, A., Rogger, M., Peth, S. & Blöschl, G. (2018). Does soil compaction increase floods? A review. *Journal of Hydrology*, *557*, 631–642. https://doi.org/10.1016/j.jhydrol.2017.12.052

Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use and Management*, *25*, 335–345. https://doi.org/10.1111/j.1475-2743.2009.00236.x

BBodSchG (1998). Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten. Gesetz zum Schutz des Bodens vom 17.03.1998 (German Federal Soil Protection Law), BGB1, p. 502.

Berisso, F. E., Schjønning, P., Keller, T., Lamandé, M., Etana, A., de Jonge, L. W., … Forman, J. (2012). Persistent effects of subsoil compaction on pore characteristics and functions in a loamy soil. *Soil & Tillage Research*, *122*, 42–51. https://doi.org/10.1016/j.still.2012.02.005

Bertolino, A. V. F. A., Fernandes, N. F., Miranda, J. P. L., Souza, A. P., Lopes, M. R. S. & Palmieri, F. (2010). Effects of plough pan development on surface hydrology and on soil physical properties in Southeastern Brazilian plateau. *Journal of Hydrology*, *393*, 94–104. https://doi.org/10.1016/j.jhydrol.2010.07.038

Beylich, A., Oberholzer, H.-R., Schrader, S., Höper, H. & Wilke, B.-M. (2010). Evaluation of soil compaction effects on soil biota and soil biological processes in soils. *Soil and Tillage Research*, *109*(2), 133–143. https://doi.org/10.1016/j.still.2010.05.010

BKG (Bundesamt für Kartographie und Geodäsie) (2010). Vector data of the digital landscape model 1:250.000.

Blume, H.-P. & Fleige, H. (2016). Soil development and soil classification. In H.-P. Blume, G. W. Brümmer, H. Fleige, R. Horn, E. Kandeler, R. Kögel-Knabner, K. Stahr & B.-M. Wilke (Eds.), *Scheffer/Schachtschabel soil science* (pp. 285–389). Berlin, Heidelberg: Springer-Verlag.

Bryk, M. (2016). Macrostructure of diagnostic B horizons relative to underlying BC and C horizons in Podzols, Luvisol, Cambisol, and Arenosol evaluated by image analysis. *Geoderma*, *263*, 86–103. https://doi.org/10.1016/j.geoderma.2015.09.014

Colombi, T., Torres, L. C., Walter, A. & Keller, T. (2018). Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth – A vicious circle. *Science of the Total Environment*, *626*, 1026–1035. https://doi.org/10.1016/j.scitotenv.2018.01.129

Cui, J., Askari, M. S. & Holden, N. M. (2014). Visual Evaluation of Soil Structure Under Grassland management. *Soil Use and Management*, *30*(1), 129–138. https://doi.org/10.1111/sum.12100

Dörner, J. & Horn, R. (2006). Anisotropy of pore functions in structured Stagnic Luvisols in the Weichselian moraine region in N Germany. *Journal of Plant Nutrition and Soil Science*, *169*, 213–220. https://doi.org/10.1002/jpln.200521844

Dörner, J. & Horn, R. (2009). Direction-dependent behaviour of hydraulic and mechanical properties in structured soils under conventional and conservation tillage. *Soil & Tillage Research*, *102*, 225–232. https://doi.org/10.1016/j.still.2008.07.004

Ehlers, W., Köpke, U., Hesse, F. & Böhm, W. (1983). Penetration Resistance and Root Growth of Oats in tilled and untilled loess soil. *Soil & Tillage Research*, *3*, 261–275. https://doi.org/10.1016/0167-1987(83)90027-2

FAO (2006). *World Soil Resources Reports: Guidelines for soil description*. Rome, Italy.

FAO (2015). *World Reference Base for Soil Resources (WRB) 2014, update 2015*. FAO, Italy, Rome.

Fleige, H., Hartmann, P., Duttmann, R., Bach, M., Gebhardt, S. & Horn, R. (2006). Soils of the sandur plain ("Lower Geest") in the Northwest of Schleswig-Holstein / Germany – The region of "Goldelund" as an example. In: Horn, R., Fleige, H., Peth, S. (Eds.): Soils and Landuse Management Systems in Schleswig-Holstein (Germany) - Guide of ISTRO Excursion 2006. Schriftenreihe Institut für Pflanzenernährung und Bodenkunde, Nr. 72, 12–19.

Gebhardt, S., Fleige, H. & Horn, R. (2009). Effect of compaction on pore functions of soils in a Saalean moraine landscape in North Germany. *Journal of Plant Nutrition of Soil Science*, *172*(5), 688–695. https://doi.org/10.1002/jpln.200800073

Goeck, J., Cordsen, E., Geisler, G. & Blume, H. P. (1988). Einfluss der Erosion auf die Standortproduktivität im Silomaisanbau. *Journal of Agronomy and Crop Science*, *161*(1), 57–64. ISSN0931-2250.

Hamza, M. A. & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil & Tillage Research*, *82*, 121–145. https://doi.org/10.1016/j.still.2004.08.009

Hartge, K. H. (1966). Ein Haubenpermeameter zum schnellen Durchmessen zahlreicher Stechzylinderproben. *Zeitschrift Für Kulturtechnik Und Flurbereinigung*, *7*, 155–163.

Hartge, K. H. & Horn, R. (2016). *Essential soil physics*. Stuttgart: Schweizerbart Publications.

Hartmann, P., Zink, A., Fleige, H. & Horn, R. (2012). Effect of Compaction, Tillage and Climate Change on Soil Water Balance of Arable Luvisols in Northwest Germany. *Soil & Tillage Research*, *124*, 211–218. https://doi.org/10.1016/j.still.2012.06.004

Holthusen, D., Fleige, H., Brandt, A., Zink, A., Horn, R. & Reichert, J. (2018). Soil functions and in situ stress distribution in subtropical soils as affected by land use, vehicle type, tire inflation pressure and plant residue removal. *Soil & Tillage Research*, *184*, 78–92. https://doi.org/10.1016/j.still.2018.07.009

Holthusen, D., Neugebauer, T., Burbaum, B., Fleige, H. & Horn, R. (2015). Brauneisengleye in Schleswig-Holstein – auf der Fährte des Raseneisensteins. *Natur- Und Landeskunde*, *122*, 33–43.

Horn, R. & Fleige, H. (2003). A method for assessing the impact of load on mechanical stability and on physical properties of soils. *Soil & Tillage Research*, *73*, 89–99. https://doi.org/10.1016/S0167-1987(03)00102-8

Horn, R. & Fleige, H. (2009). Risk assessment of subsoil compaction for arable soils in Northwest Germany at farm scale. *Soil & Tillage Research*, *102*, 201–208. https://doi.org/10.1016/j.still.2008.07.015

Horn, R., Mordhorst, A., Fleige, H., Zimmermann, I., Burbaum, B., Filipinski, M. & Cordsen, E. (2019). Soil type and land use effects on tensorial properties of saturated hydraulic conductivity in northern Germany. *European Journal of Soil Science*, *1–11*, https://doi.org/10.1111/ejss.12864

Horn, R. & Peth, S. 2011. Mechanics of unsaturated soils for agricultural applications. In P. M. Huang, Y. Li & M. E. Sumner (Eds.), *Handbook of soil sciences*, 2nd edn (pp. 1–30). Boca Raton, FL: CRC Press.

Horn, R., Way, T. & Rostek, J. (2003). Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. *Soil & Tillage Research*, *73*, 101–106. https://doi.org/10.1016/S0167-1987(03)00103-X

.IPCC (Intergovernmental Panel on Climate Change) (2018). Global Warming of 1.5 °C. Summary for Policymakers (Special Report), 32 p, Switzerland. ISBN 978-92-9169-151-7.

Janetzko, P. & Fleige, H. (2010). Watten und Marschen Nordwestdeutschlands, Teil Schleswig-Holstein. In: Blume, H.-P., Felix-Henningsen, P., Frede, H.-G., Guggenberger, G., Horn, R., Stahr, K. (Eds). Handbuch der Bodenkunde. 33. Ergänzungslieferung, 01/10, 1–22.

Jones, R. J. A., Spoor, G. & Thomasson, A. J. (2003). Vulnerability of subsoils in Europe to compaction: A preliminary analysis. *Soil & Tillage Research*, *73*, 131–143. https://doi.org/10.1016/S0167-1987(03)00106-5

Keller, T., Sandin, M., Colombi, T., Horn, R. & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*, *194*, 167–1987. https://doi.org/10.1016/j.still.2019.104293

Koppi, A. J., Douglas, J. T. & Moran, C. J.. (1992). An image analysis evaluation of soil compaction in grassland. *Journal of Soil Science*, *42*, 15–25. https://doi.org/10.1111/j.1365-2389.1992.tb00116.x

Kretzschmar, R. (1996). *Kulturtechnisch-bodenkundliches Praktikum. Ausgewählte Labor- und Feldmethoden. Eine Anleitung zum selbstständigen Arbeiten an Boden und Gewässern in zwei Banden*, 9. Aufl., Akademisches Institut für Wasserwirtschaft und Landschaftsökologie der Christian-Albrechts-Universität Kiel.

Kuncoro, P. H., Koga, K., Satta, N. & Muto, Y. (2014). A study on the effect of compaction on transport properties of soil gas and water I: Relative gas diffusivity, air permeability, and saturated hydraulic conductivity. *Soil & Tillage Research*, *143*, 172–179. https://doi.org/10.1016/j.still.2014.02.006

Lebert, M. (2010). Entwicklung eines Prüfkonzeptes zur Erfassung der tatsächlichen Verdichtungsgefährdung landwirtschaftlich genutzter Böden, *Texte* 51, Umweltbundesamt, Dessau-Roßlau. ISSN 1862-4804.

Lipiec, J., Świeboda, R., Chodorowski, J., Turski, M. & Hajnos, M. (2018). Pore size distribution and stability of ortstein and overlying horizons in podzolic soils under forest. *Geoderma*, *310*, 138–142.

Menezes, A. S., Alencar, T. L., Assis Júnior, R. N., Toma, R. S., Romero, R. E., Costa, M. C. G., … Mota, J. C. A. (2018). Functionality of the porous network of Bt horizons of soils with and without cohesive character. *Geoderma*, *313*, 290–297. https://doi.org/10.1016/j.geoderma.2017.11.005

Moffat, A. J. (1991). Forestry and soil protection in the UK. *Soil Use and Management*, *7*(3), 145–150. https://doi.org/10.1111/j.1475-2743.1991.tb00866.x

Mordhorst, A. (2009). Zeitabhängige Strukturbildung bei biologisch-dynamischer Bodenbewirtschaftung mit leichten Maschinen und Zugpferden. Masterthesis, Uni Kiel.

Mordhorst, A., Fleige, H., Zimmermann, I., Burbaum, B., Filipinski, M., Cordsen, E. & Horn, R. (2018). Organische Kohlenstoffvorräte von Bodentypen in den Hauptnaturräumen Schleswig-Holsteins (Norddeutschland). Organic carbon stocks of soil types in the geological regions of Schleswig-Holstein (Northern Germany). *Die Bodenkultur: Journal of Land Management, Food and Environment*, *69*, 85–95. https://doi.org/10.2478/boku-2018-0008

Mossadeghi-Björklund, M., Jarvis, N., Larsbo, M., Forkmann, J. & Keller, T. (2018). Effects of compaction on soil hydraulic properties, penetration resistance and water flow patterns at the soil profile scale. *Soil Use and Management*, *35*(3), 367–377. https://doi.org/10.1111/sum.12481

Müller, W. (1955). Verdichtungserscheinungen in Marschböden. *Zeitschrift Für Pflanzenernährung, Düngung, Bodenkunde*, *71*(3), 225–232. https://doi.org/10.1002/jpln.19550710305

Müller, W. (1994). Zur Genese der Marschböden. I. Einfluss von Sediment- und Bodengefüge. *Journal of Plant Nutrition and Soil Science*, *157*, 1–9. https://doi.org/10.1002/jpln.19941570102

Needham, P., Scholz, G. & Moore, G. (2004). Ch. 4 Physical restrictions to root growth. 4.1 Hard layers in soils. 4.2 Subsurface compaction. In: Moore, G. (Ed). Soil guide: a handbook for understanding and managing agricultural soils, pp. 109–124, Dept of Agriculture, Western Australia. Bulletin No. 4343.

Pulido-Moncada, M., Munkholm, L. J. & Schjønning, P. (2019). Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. *Soil & Tillage Research*, *186*, 300–309. https://doi.org/10.1016/j.still.2018.11.005

Richter, F.-H., Fleige, H., Blume, H.-P. & Horn, R. (2007). Bodengesellschaften von geomorphen Einheiten unter Berücksichtigung des Gefügestils im Stormarner Jungmoränengebiet (Brandenburger Stadium) in Nordwestdeutschland. *Journal of Plant Nutrition and Soil Science*, *170*(5), 682–692. 10/1002/jpln.200700110

Riggert, R., Fleige, H., Kietz, B., Gaertig, T. & Horn, R. (2016). Stress Distribution under Forestry Machinery and Consequences for Soil Stability. *Soil Science Society of America Journal*, *80*(1), 38–47. https://doi.org/10.2136/sssaj2015.03.0126

Riggert, R., Fleige, H., Kietz, B., Gaertig, T. & Horn, R. (2017). Dynamic stress measurements and the impact of timber harvesting on physical soil properties. *Australian Forestry*, *80*(4), 255–263. https://doi.org/10.1080/00049158.2017.1347981

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., … Böschl, G. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water Resources Research*, *53*(7), 5209–5219. https://doi.org/10.1002/2017WR020723

Seehusen, T., Børresen, T., Rostad, B. I., Fleige, H., Zink, A. & Riley, H. (2014). Verification of traffic-induced soil compaction after long-term ploughing and 10 years minimum tillage on clay loam soil in South-East Norway. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, *64*(4), 312–328. https://doi.org/10.1080/09064710.2014.907582

UBA (Umweltbundesamt) (2004). Ableitung von Kriterien zur Charakterisierung einer schädlichen Bodenveränderung, entstanden durch nutzungsbedingte Verdichtung von Böden / Regelungen zur Gefahrenabwehr, ed. I. f. B. u. B. d. B. f. Landwirtschaft: Umweltbundesamt.

Wiermann, C., Werner, D., Horn, R., Rostek, J. & Werner, B. (2000). Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatments in Germany. *Soil & Tillage Research*, *53*, 117–128. https://doi.org/10.1016/S0167-1987(99)00090-2

Zink, A., Fleige, H., Gebhardt, S. & Horn, R. (2013). Verification of Subsoil Compaction on Cable Construction Sites. *Advances in Geoecology*, *42*, 148–163.

Zink, A., Fleige, H. & Horn, R. (2010). Load Risks of Subsoil Compaction and Depths of Stress Propagation in Arable Luvisols. *Soil Science Society of America Journal*, *74*, 1733–1742. https://doi.org/10.2136/sssaj2009.0336

Zink, A., Fleige, H. & Horn, R. (2011). Verification of harmful subsoil compaction in loess soils. *Soil & Tillage Research*, *114*(2), 127–134. https://doi.org/10.1016/j.still.2011.04.004