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 (Ks) and effective bulk density (ρBeff) 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.-%, Ks < 10 cm day⁻¹, ρBeff > 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 Ks 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 ρBeff, 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.

Key words
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 (Ks) in the subsoil,
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 (hard-pans) of soil types like Orthsteinic 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 irreversibility of 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 ($\leq 40$ 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 (Ks), and (effective) bulk density (ρeff). 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 km²), the sandy outwash region called “Lower Geest” (2,010 km²), the Saalian glacial region (older moraine area or “Higher Geest”, 3,766 km²) in the centre, and the marshland with alluvial deposits in the west (2,854 km²).

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 I” (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](image-url)
Bulk density ($\rho_B$), effective bulk density ($\rho_{Beff}$), saturated hydraulic conductivity ($K_s$) and air capacity (AC) (air-filled pore volume at -6 kPa) were determined on undisturbed soil samples (100 cm³), while grain size distribution (among others) was analysed on disturbed samples. $\rho_B$ is defined by the oven-dried soil mass (105°C) per sample volume (100 cm³), whereas the $\rho_{Beff}$ 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). $\rho_{Beff}$ is calculated as follows (Ad-hoc-AG Boden, 2005; FAO, 2006):

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

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). $\rho_{Beff}$, $K_s$ 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 geological regions is given in Mordhorst et al. (2018). This amounted to 342 soil profiles, which were extracted from the database (that contained > 900 soil profiles). They were evaluated with respect to the soil physical parameters, which were bulk density and effective bulk density (ρB and ρBeff), air capacity (AC) and saturated hydraulic conductivity (Ks) 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 stigmatic 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 Ks: 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 I: AC and Ks do not exceed (are greater than) the critical threshold values
- Classes II and III: AC or Ks exceed (is smaller than) the critical threshold value
- Class IV: AC and Ks exceed (are smaller than) the critical threshold values (potentially harmful subsoil compaction)

AC and Ks 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 (ρB or ρBeff), 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, ρBeff 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 Ks (10 cm day⁻¹) as action values,
while the critical threshold value for $\rho_{\text{Beff}}$ (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 ($\rho_b$), 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 | Glacial loam | “Higher” and “Lower Geest” | 46 | < 0.3 |
| Sum                   | | | 6,579 | 42 |

*aHolthusen, Neugebauer, Burbaum, Fleige, and Horn (2015).
C horizons in the coastal marshland areas, showed “low” to “medium” \( \rho_B \), “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” \( \rho_B \) 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”) \( \rho_B \) 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” \( \rho_B \) 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 \( \rho_{\text{Beff}} \) (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 \( \rho_{\text{Beff}} \) 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” \( \rho_{\text{Beff}} \), 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 Arenosols 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) B(2)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.-%, \( K_s < 10 \text{ cm day}^{-1} \)). 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

| Soil type according to WRB (FAO, 2015) | Rel. Area [%] | Horizon (FAO, 2006) | n | Clay content Mean [%] | SEM [%] | \( \rho_B \) Mean [g cm\(^{-3}\)] | SEM [g cm\(^{-3}\)] | \( \rho_{\text{Beff}} \) 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(1)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             |

Abbreviations: \( \rho_B \), Bulk density; \( \rho_{\text{Beff}} \), 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 $\rho_{Beff}$ with a threshold value of > 1.7 g cm$^{-3}$, should be considered. The investigated sandy soils had mean $\rho_{Beff}$ 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 $\rho_{Beff}$ were found in Anthrosols and (Gleyic) Podzols and only 5%–13% of the samples exceed the critical threshold. In contrast, mean $\rho_{Beff}$ (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%

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**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)
(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 mostly 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 ($< 100 \mu m$) 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 colluvial 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
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
anthropic compaction by agricultural or forestry use. Therefore, the calculated subsoil compaction status (derived by the soil indicator parameters, AC and Kc) 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 (≤13% in Class IV). In these latter soils, less than 1/5 of ρBett 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.

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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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