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The effect of raised groundwater tables on load-bearing capacity of peat grassland on a dairy farm

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ABSTRACT

Dutch agricultural peatlands are typically drained to promote production and trafficability, however, this leads to peat oxidation, CO_2 emissions and soil subsidence. Rewetting peatlands by raising the groundwater table (WT) to −0.20 m reduces these environmental impacts but may compromise load-bearing capacity (LBC). An LBC of at least 0.7 MPa is required to prevent sward damage during field access, thus inadequate LBC affects optimal farm management. However, mechanisms determining LBC under a raised WT remain poorly understood. This study examined the relationships between an elevated WT (to −0.20 m, using an active water infiltration system), soil moisture content (SMC), season, grassland use (grazing or mowing), and LBC measured as penetration resistance in a four-year on-farm experiment. Biweekly measurements in spring and autumn were conducted on sixteen experimental plots. A regression model was developed, and structural equation modelling was applied to understand relationships among variables. Results showed that raising the WT decreased LBC by 1 MPa m^{-1}, but this was strongly mediated by SMC and highly dependent on season. Moreover, LBC was higher on pasture fields than silage fields. This study highlights how the complex interplay between SMC, WT, grassland use and season jointly affect the LBC of peat soils at one experimental location. Moreover, measuring impact depth was compared to penetration resistance, showing greater sensitivity under wet conditions and to variations in sward characteristics. The findings can provide input for further studies on field management decisions and compensation schemes to support a wide range of farmers to successfully farm under raised WT conditions.

1. Introduction

Approximately 500 million hectares of the world's land are covered by peatlands, of which around 12% is degraded, primarily through drainage for agricultural use and forestry (UNEP, 2022). Within the EU, even 50% of the peatlands are drained (Tanneberger et al., 2021; UNEP, 2022). In the Netherlands, peatlands account for about 8% of the total land area (Joosten, 2010), covering 290.000 ha of which 77% is used for agriculture, predominantly in the form of grassland for dairy farming (van den Akker et al., 2010). The groundwater table (WT) of these agricultural peatlands is typically drained up to 0.50 m below field level (-0.50 m) to promote grass growth and to increase load-bearing capacity (LBC) so that the land is accessible for both machinery and livestock (Poppe et al., 2021; Schothorst, 1982; van den Akker et al., 2010).

Lowering the WT in peatland results in peat decomposition through oxidation, which goes hand in hand with CO_2 emissions and soil subsidence (van Asselen et al., 2020). Globally, peatlands are responsible for 2.000 Mt of CO_2 emissions (UNEP, 2022). In the Netherlands, peatlands alone account for about 2% of the country's total anthropogenic CO_2 emissions (van den Akker et al., 2010). Moreover, drainage leads to high costs for water level management and infrastructure, and negative consequences for nature and biodiversity (van den Born et al., 2016). Additionally, the importance of conservation of peatlands is recognized because of their delivery of different ecosystem services, particularly carbon sequestration, water regulation and biodiversity (Deru et al., 2018).

Rewetting peatland by raising the groundwater level is seen as one of the primary strategies to mitigate these issues (Hendriks et al., 2007; Poppe et al., 2021; Querner et al., 2012). Current scientific insights suggest that a WT of 0.20 m below field level (-0.20 m) is the optimum in

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order to minimize soil subsidence and the inextricably linked CO_2 emissions (Evans et al., 2021; Hoving et al., 2021; Tiemeyer et al., 2020). However, raising WTs means that the load bearing capacity (LBC) may be jeopardised (Holshof et al., 2011; Janssen et al., 2023; Schothorst, 1982). LBC on peat grasslands, measured as penetration resistance, typically ranges between 0 and ca. 2 MPa, and values below 0.7 MPa are considered inadequate to prevent sward damage from livestock and machinery (Beuving et al., 1989; Scholz and Hennings, 1996; van Wijk, 1977). Insufficient LBC can hinder the timing of essential agricultural activities like slurry application, grazing, and mowing, while livestock trampling or use of heavy machinery during periods with insufficient LBC can damage the sward, ultimately reducing grass yield and quality (Bilotta et al., 2007; de Vos et al., 2010; Holshof et al., 1994; Hoving et al., 2024; Schothorst, 1982). De Vos et al. (2006) estimated that raising the WT from −0.60 to −0.40 m reduces net grass yield and decreases farm income by €222 ha^{-1} per year. Similarly, Hoving et al. (2020) estimated a reduction in farmers' labour return of up to €622 ha^{-1} per year using a pressurized submerged drainage system with active water infiltration (AWIS) to elevate the WT from −0.50 to −0.30 m. Moreover, maintaining adequate soil functioning is essential for sustaining these ecosystem services, as soil compaction can negatively affect soil biodiversity, water infiltration, root growth and nutrient cycling (Batey, 2009; Nawaz et al., 2013). Altogether, this underscores the challenges that might arise from inadequate LBC under raised WT conditions.

For organic soils, LBC is determined by the pressure needed to press a 500 mm^2 cone through the sward, using a hand-held penetrometer. Penetration resistance represents the stress required to push a cone into the soil and therefore depends on the cone tip area (Junior et al., 2014). Because the contact area of the cone is small, the measured resistance reflects local soil strength, although it is recognised as a proxy for overall soil strength and LBC (Janssen et al., 2023; Kazemian et al., 2011; Schothorst, 1982).

It is known that LBC is primarily affected by soil moisture content (SMC), with an increased SMC resulting in reduced LBC (Angers and Caron, 1998; Bilotta et al., 2007; Hoekstra et al., 2019; Holshof et al., 2011; Janssen et al., 2023; Tengbeh, 1993; Uusitalo and Ala-Ilomäki, 2013). Since a higher WT is strongly interrelated with SMC, it has been suggested that the effect of a raised WT on LBC is merely mediated through SMC (Schothorst, 1982). The relation between SMC and LBC indicates that issues are particularly likely to arise during wet periods, as observed during spring and autumn in the Netherlands. Secondly, research shows that a higher soil density, which is linked to soil texture and soil organic matter content, increases LBC (Remmelink et al., 2018; Schothorst, 1982). Lastly, vegetation can enhance LBC by an increase in above and below-ground plant material (Bilotta et al., 2007; O'Connor, 1956; Patto et al., 1978), for which tiller density or basal vegetation cover serves as a proxy (Hoekstra et al., 2019; Janssen et al., 2023). Several factors related to grassland management have been shown to influence tiller density. For instance, tiller density is lower when the sward is solely mown, in comparison to fields that are grazed (Cashman et al., 2016; Evans et al., 1998). However, to the best of our knowledge, the combined effects of all these variables on LBC has not been studied.

Since the contact area of a penetrometer is small, penetration resistance may not represent the impact of treading cattle on the sward well. Therefore, Janssen et al. (2023) developed a method that measures LBC as impact depth, thus simulating the impact of treading cattle on the sward, using a weight resembling a cow hoof. The greater contact area of the cow hoof may be influenced more strongly by changes in vegetation structure than a penetrometer. Janssen et al. (2023) concluded that measuring impact depth has practical value because of easy visualization and interpretation of the methodology (i.e. how much grazing livestock will penetrate a sward) by farmers, but the sensitivity of the method has to be further determined.

The aim of this study was threefold. The first objective was to clarify and quantify the effect of a raised WT on the LBC of agricultural peatlands, using penetration resistance. Furthermore, we assessed how SMC, spring and autumn conditions, and grassland use (grazing or mowing) influence this relationship. Lastly, we aimed to compare the sensitivity of impact depth and penetration resistance to these variables, and to evaluate under what conditions the cow-hoof method may offer added value. To this end, we conducted an on-farm experiment, comparing fields with high and low groundwater levels under two grassland use strategies – mowing only (silage fields) and combined grazing and mowing (pasture fields) (Figure S1). Field measurements were conducted in spring and autumn.

We hypothesised that (i) fields with a raised WT have a higher SMC, which results in a lower LBC; (ii) LBC is lower in spring than in autumn; (iii) silage fields have a lower basal vegetation cover compared to pasture fields, which will lead to a lower LBC; and (iv) impact depth is more sensitive under relatively wet conditions, and to variations in basal cover compared to penetration resistance.

2. Materials and methods

2.1. Area and experimental setup

An on-farm experiment was carried out at the Knowledge Transfer Centre (KTC) Zegveld experimental farm (52°08′25.8"N 4°50′19.7"E), located on drained peat soil (Terric Histosol, WRB; IUSS Working Group WRB, 2022) in the western peatland region of the Netherlands (44% soil organic matter, 26% clay, 15% silt, 15% sand, determined at 0–0.10 m). The soil contained approximately 20.7 g N kg^{-1} dry soil and 270 mg P_{AL}-phosphate kg^{-1} dry soil and had an average bulk density of 0.6 g cm^{-3} at 25–75 mm soil depth. The peat profile consists of Sphagnum peat in the upper layers, underlain by sedge peat, fen peat, and wood peat, with a total peat thickness of 6–7 m. Beneath the peat layer, a sandy mineral subsoil is present (Schothorst, 1982). The fields at the location are separated by ditches and have a width of 30–60 m. The average WT in the region ranges from −0.50 to −0.35 m (Hoving et al., 2021). The experimental period spanned from spring 2020 to autumn 2024, with 2020 being designated as a transitional year for adjustments, used to evaluate and adjust water management strategies to achieve more consistent groundwater levels across all monitoring plots.

The design included four treatments on sixteen monitoring plots of 10 m x 10 m (100 m^2) (Table 1). For the study, the WT of the high-water fields was raised, using AWIS to maintain raised groundwater

Table 1
Details of the experimental set-up, showing the average (low-water fields) and target (high-water fields) groundwater table (WT), grassland use (G: grazing, M: mowing), field areas and number of monitoring plots for the low-water (reference) and high-water table treatments on pasture fields and silage fields. In 2023 an extra plot was added to better account for variation between different fields, giving a total of four monitoring plots for the low-water pasture fields. Low-water fields were grazed by Holstein Frisian cows only, while half of the high-water pasture fields were grazed by Jersey cows and the other half by Holstein Frisian cows to assess differences in sward damage related to cow breed. To this end two sets of monitoring plots were established on the high-water pasture fields. However, since there were no significant differences in the parameters related to LBC, these plots were jointly analysed in this paper. The presence of Jersey cows on part of the high-water fields also resulted in a slightly higher average stocking density compared to the low-water fields.

	Low-water fields		High-water fields	
WT (cm)	-50		-20	
Stocking rate (cows ha^{-1})	2.3		2.7	
Grassland use	Pasture fields (G and M)	Silage fields (only M)	Pasture fields (G and M)	Silage fields (only M)
Total area (ha)	15.4	7.1	15.2	7.4
Number of monitoring plots	3–4	3	6 (2 × 3)	3 (3)

conditions. The drainage pipes of this system are linked to a water reservoir, which pumps water in and out actively to create a difference in pressure between surface water table and WT. This leads to infiltration of water during dry periods (when the WT is low), and drains water during wet periods (when the WT is high), thus levelling and stabilizing the WT at a target level (Hoving et al., 2009). For this system, parallel drainage pipes were installed in 2019 at 6 m spacing. At the beginning of 2023, additional drains were installed, reducing the spacing to 3 m to maintain the groundwater table closer to the target level of −0.20 m.

Besides a target WT of −0.20 m for high-water fields, ditch water levels were raised to −0.20 m in the high-water fields. The low-water fields served as a reference and had no active drainage systems in place to reflect the current practice in dairy farming in the region, resulting in a WT of −0.50 m on average. Monitoring wells were installed throughout all fields to enable measurement of the WT, and for each experimental plot, one representative monitoring well was used to determine the WT.

Silage fields were exclusively mowed, whereas the pasture fields were primarily grazed and occasionally mowed. The grazing season generally extended from April to October. Average stocking density was 2.3 cows ha^{-1} on the low-water fields and 2.7 cows ha^{-1} on the high-water fields, where the use of smaller and lighter Jersey cows allowed for a higher stocking density (Table 1). Silage fields were cut four (2021, 2023, 2024) to five (2022) times per year, depending on grass growth and weather conditions. Pasture fields were cut one to three times annually and were additionally grazed, again depending on grass growth. All fields were fertilized using both artificial fertilization (70–85 kg total N ha^{-1}) and cattle slurry (173 kg total N ha^{-1}), distributed over four applications per growing season.

2.2. Data collection

At the start of each year, the specific location of each monitoring plot was moved to a new location within the same field, to prevent soil disturbance through repeated measurements. Measurements were taken during spring and autumn, which are the periods that are considered critical for LBC due to relatively wet conditions. Each year in spring, measurements started in the week of the first slurry application of the year, usually in February or March, and continued until the LBC was deemed adequate for grazing (> 0.7 MPa). In autumn, measurements began in September, when precipitation increased and stopped when LBC fell below the threshold (< 0.7 MPa), or in practice, when the grazing season ended. During these periods, it was the aim to conduct measurements biweekly, resulting in a total of 44 measurement occasions (Table S1).

Penetration resistance (MPa) was assessed using a penetrometer (Eijkelkamp, The Netherlands) with a cone diameter of 500 mm^2 and a 60º apex angle. In each plot, 15 measurements were taken and averaged to determine the maximum force required to press the cone through the sward and top few centimetres of the soil.

Impact depth (mm) was measured on 36 out of 44 measurement occasions using the cow-hoof method as described by Janssen et al. (2023). An 8 kg cylindrical weight with a diameter of 68 mm was dropped from a height of 0.60 m, and impact depth was expressed as negative values (mm below the surface), with more negative values indicating deeper penetration below the soil surface. In each plot, 10 measurements were taken and averaged.

The WT was measured during each measurement round by lowering a digital weighted measuring tape into one representative monitoring well for each monitoring plot. Monitoring plots were consistently located within 20 m of a monitoring well. Missing WT measurements (in total 119/360 measurements in 2020, 18/378 measurements in 2021, 19/518 measurements in 2022, 12/465 measurements in 2023 and 2/405 measurements in 2024) due to occasional technical or recording errors during field monitoring were interpolated from drainpipes within the same treatment.

Gravimetric SMC (%) was measured on each occasion by collecting approximately 20 soil cores per plot at 0–0.10 m using a grassland auger (Eijkelkamp, The Netherlands) and drying the samples at 105°C for 24 h to determine the soil dry weight and to calculate the weight of water per 0.100 kg soil (Reynolds, 1970).

Tiller density was evaluated by measuring basal cover of vegetation, using a point intercept method (Janssen et al., 2023; Levy and Madden, 1933). A 10-point point frame consisting of a horizontal PVC tube with 10 spokes placed at 0.10 m intervals was used and for each spoke was recorded whether it touched bare soil or the base of a grass tiller. Basal cover was calculated as the percentage of total contacts with grass tillers, representing the fraction of ground covered by vegetation. Measurements were repeated 10 times per plot. Basal cover was measured twice a year, once in spring, and once in autumn, and the basal cover for the other measurement rounds was acquired by interpolation.

Precipitation data were collected at the KNMI precipitation station Zegveld, located 5.5 km from the experimental location. From April 28th 2022 onward, daily precipitation data were recorded at the experimental location, using an automated on-site weather station (AgroExact, the Netherlands). Evapotranspiration data for the whole experimental period was obtained from the KNMI weather station de Bilt, located 23 km from the experimental location (KNMI, n.d). Daily cumulative precipitation excess (precipitation minus evapotranspiration) was calculated for each experimental year, starting on April 1 and ending on October 31 each year, which was the period the grazing season took place (Fig. 1a). Monthly precipitation showed large variation over the experimental years (Fig. 1b, Table S2). Precipitation of 2021 was closest to the long-term average, and the year 2022 was considered exceptionally dry in comparison to the long-term average. The winter of 2023 and the following spring of 2024 were exceptionally wet. Average monthly temperatures were all close to the long-term average (Table S2, Figure S2).

2.3. Statistical analysis

All data were analysed using R version 4.4.1 (R Core Team, 2021), using a significance level of 0.05, unless specified otherwise.

Descriptive statistics were used to assess trends and retrieve Pearson correlation coefficients between variables. To derive the threshold level for impact depth based on the threshold value for penetration resistance three candidate models were evaluated. Among the three models, the one with the lowest Akaike Information Criterion (AIC) value was selected as the best-fitting model (Eq. 1).

$$ID = \beta 0 + \beta 1 \times \exp(\beta 2 \times PR) \quad (1)$$

Where ID = Impact depth (mm), and PR = penetration resistance (MPa).

Structural equation modelling (SEM) was performed to understand the relationships between penetration resistance and predicting variables. Data points with an SMC above 248% were removed, as penetration resistance no longer decreased with increasing SMC but instead reached a plateau. Not taking these values into account for data analysis allowed us to focus on the portion of the data where variations in SMC still influenced penetration resistance. A hypothetical model was constructed based on theory and prior analysis, and piecewise SEM was applied using the R package 'piecewiseSEM' (Lefcheck et al., 2024). Relationships were added based on the tests of directed separation which evaluate the significance of missing relationships in the model when theoretically justified, and removed when they were not significant. Interaction terms and random effects were excluded to simplify the model and improve interpretability. Path diagrams were visualized using the 'semPlot' package in R (Epskamp et al., 2022), for which data were standardized (mean = 0, standard deviation = 1), to allow direct comparison of variables. The developed SEM for penetration resistance consisted of four regression models (Eqs. 2–5), with penetration

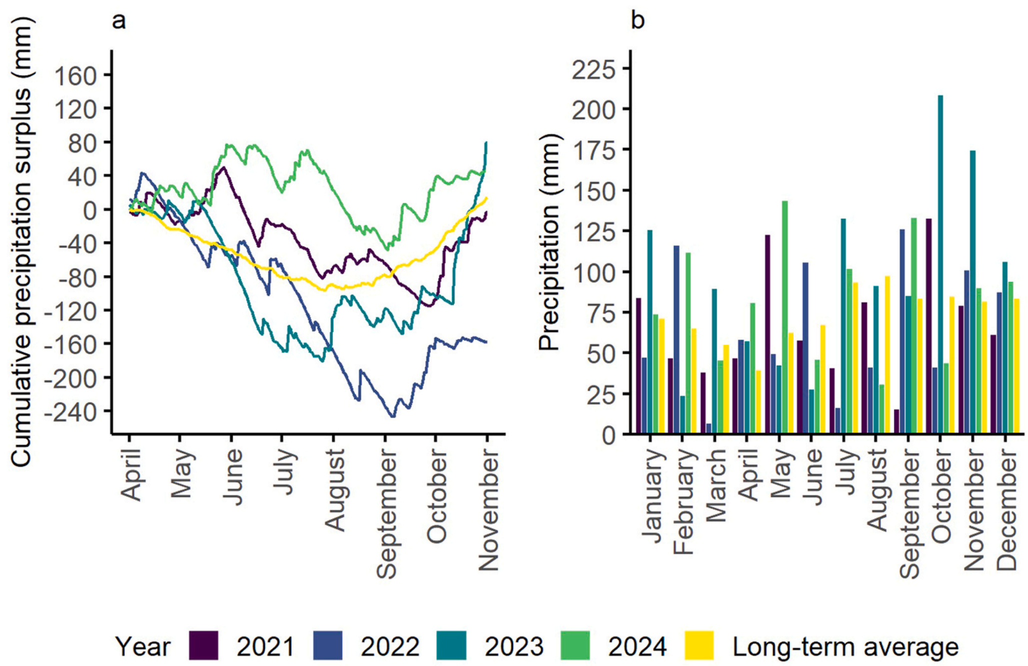

Fig. 1. Cumulative precipitation surplus, measured from April 1 to October 31 per experimental year (a), and monthly sum of precipitation per experimental year (b) in comparison with the long-term average (2000–2020).

resistance, SMC, basal cover, and WT as response variables.

$$PR = \beta0 + \beta1 \times WT + \beta2 \times SMC + \beta3 \times BC + \beta4 \times Season \quad (2)$$

$$SMC = \beta1 \times WT + \beta2 \times Season + \beta3 \times GU \quad (3)$$

$$BC = \beta0 + \beta1 \times GU \quad (4)$$

$$WT = \beta0 + \beta1 \times AWIS \quad (5)$$

Where PR = penetration resistance (MPa), SMC = soil moisture content (% on 0–0.10 m), WT = groundwater table (m below field level), BC = basal cover (%), Season = season (spring or autumn), and GU = grassland use (silage or pasture fields).

Two regression models with penetration resistance as a response variable were developed, using the lme4 package in R (Bates et al., 2015). Again, the reduced dataset was used, omitting data points with an SMC above 248%. In the first model, WT, season, basal cover, and all two-way interactions between variables were included. Random effects were included for the factor Field to account for variability in e.g. soil characteristics across fields, and for the factor Year to capture overall temporal variations in e.g. weather circumstances and management practices. Exhaustive model selection (all-subsets selection) was used to evaluate all possible combinations of variables. For each model, the AICc, marginal R^2 and conditional R^2 were calculated to assess model fit, using the MuMIn package in R (Bartoń, 2024), and select the best performing model (Eq. 6, Model A1). From this model, insignificant effects were removed. Variance inflation factors (VIF) were used to assess multicollinearity.

$$PR = \beta0 + \beta1 \times WT + \beta2 \times Season + \beta3 \times BC + \beta4 \times (WT \times Season) + \beta5 \times (BC \times Season) + u(Field) + u(Year) + \varepsilon \quad (6)$$

$$PR = \beta0 + \beta1 \times WT + \beta2 \times SMC + \beta3 \times Season + \beta4 \times BC + \beta5\,(WT \times SMC) + \beta6 \times (SMC \times Season) + \beta7 \times (BC \times Season) + u(Field) + u(Year) + \varepsilon \quad (7)$$

Where PR = penetration resistance (MPa), SMC = soil moisture content (%), WT = groundwater table (m below field level), BC = basal cover (%), Season = season (spring or autumn), u(Field) and u(Year) are random intercepts for field and year, and ε is the residual error.

In the second regression model (Eq. 7, Model B1), SMC was added as an explanatory variable, including its interactions with other variables. Model selection followed the same method as for model A1. For visualisation of this model, season-specific SMC tertiles (0–33.3%, 33.3–66.7%, 66.7–100%) were defined and model predictions were calculated at the median SMC within each tertile.

To compare penetration resistance and impact depth, a SEM and two regression models for impact depth (Model A2 and B2, Eqs. 8 and 9, respectively) were developed, using the same methods as described for penetration resistance.

$$ID = \beta0 + \beta1 \times WT + \beta2 \times Season + \beta3 \times BC + \beta4 \times (WT \times Season) + \beta5 \times (BC \times Season) + u(Field) + u(Year) + \varepsilon \quad (8)$$

$$ID = \beta0 + \beta1 \times WT + \beta2 \times SMC + \beta3 \times Season + \beta4 \times BC + \beta5 \times (SMC \times Season) + \beta6\,(BC \times Season) + u(Field) + u(Year) + \varepsilon \quad (9)$$

The developed SEM for impact depth used the same model structure as for penetration resistance (Eqs. 4–7), substituting impact depth as the main response variable in Eq. 4. Since there was no pronounced plateau in impact depth, the complete dataset was used for the regression analysis for impact depth. The generated output was used to compare the sensitivity of impact depth versus penetration resistance to the different variables.

3. Results

3.1. General trends

Over the four years, the mean WT during the measurement period (i.e., spring and autumn) of the high-water and low-water fields were −0.18 and −0.36 m, respectively. While the average WT of −0.18 m on high-water fields applied to both spring and autumn, on low-water fields, the average WT was −0.32 m in spring and −0.42 m in autumn. The annual average WT of the high-water fields ranged from −0.14 (year 2024) to −0.23 m (2023), and of the low-water fields from −0.26 (2024) to −0.42 m (2022). There was more variation in the WT in autumn compared to spring (Fig. 2a). There was a negative correlation between WT and penetration resistance, and WT and impact depth

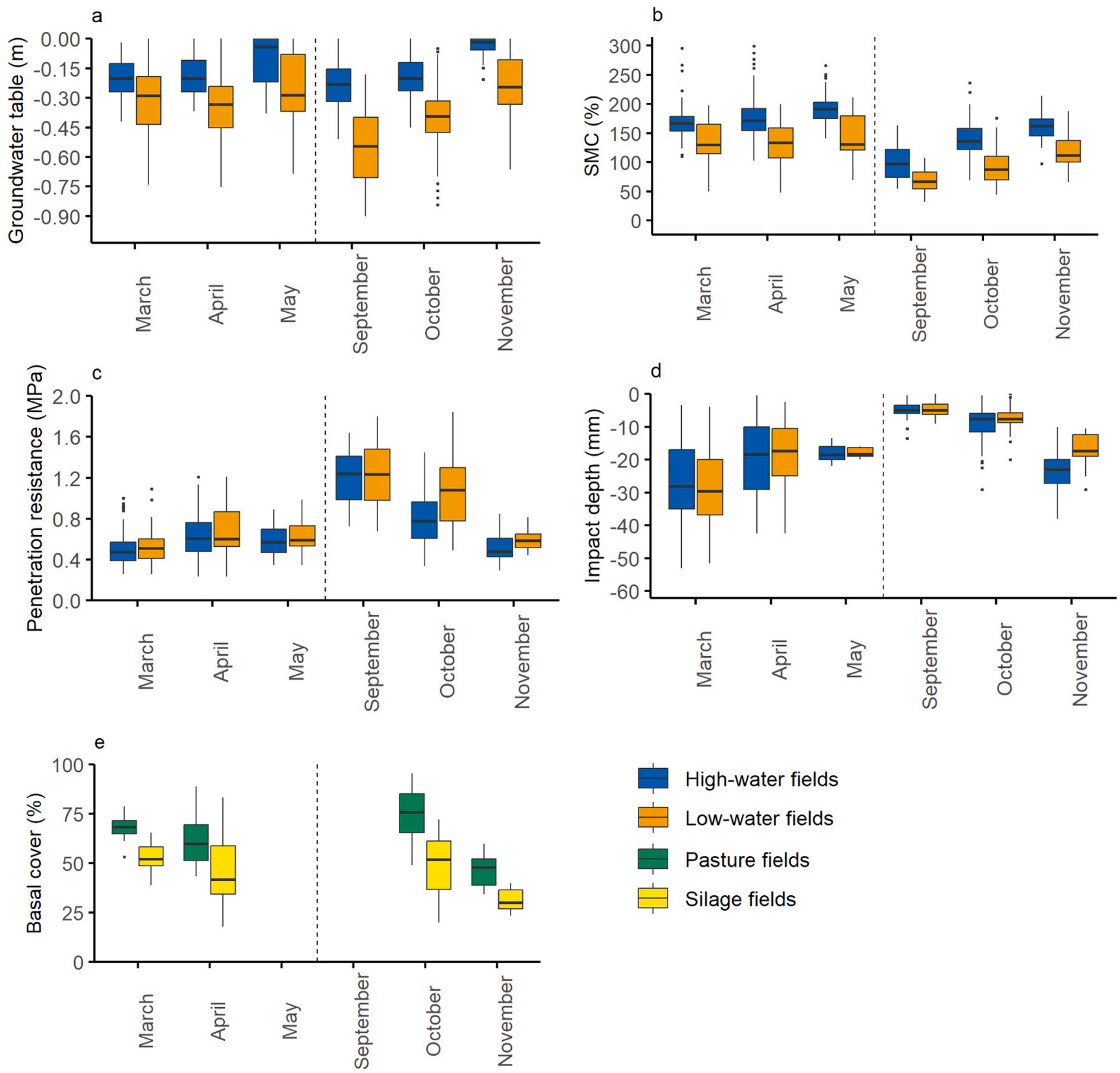

Fig. 2. Trends in (a) groundwater table (WT), (b) soil moisture content (SMC), (c) penetration resistance and (d) impact depth across WT categories (high-water versus low-water fields) and (e) basal cover for the pasture and silage fields for all months across the 4 years. The dotted line indicates the separation between measurements taken in spring (March, April, May) and autumn (September, October, November). Boxplots show the median (horizontal line), interquartile range (box; 25th - 75th percentile), and whiskers representing the range of data within 1.5 times the interquartile range. Points beyond the whiskers indicate outliers.

Table 2
Correlations between Penetration resistance, impact depth, soil moisture content (SMC), groundwater table (WT) and basal cover across 4 years. $p < 0.001$ = '***', $p < 0.01$ = '**', $p < 0.05$ = '*'. See Tables S3-S8 for correlations per measurement year and season.

	Impact depth	SMC	WT	Basal cover
Penetration resistance	0.71***	-0.63***	-0.45***	0.19***
Impact depth		-0.53***	-0.27***	0.42***
SMC			0.66***	0.08*
WT				0.23***

(Table 2).

We observed a higher SMC (0–0.10 m) in high-water fields than in low-water fields (Fig. 2b), and penetration resistance and impact depth were negatively correlated to SMC, while SMC was positively correlated to WT (Table 2).

The difference in penetration resistance between low-water fields and high-water fields was greater in autumn compared to spring (Fig. 2c). Penetration resistance increased and impact depth became less negative over time during spring, and a reversed pattern was observed over time in autumn (Figs. 2c and 2d). A positive correlation was observed between penetration resistance and impact depth, indicating that higher penetration resistance was associated with shallower impact depth. This was consistent over seasons and years, with a stronger correlation in the exceptional wet year 2024 (Tables S3-S8).

The average basal cover was 65% for pasture fields and 44% for silage fields (Fig. 2e). Basal cover showed a positive correlation with both penetration resistance and impact depth (Table 2).

3.2. SEM – exploring underlying relationships of penetration resistance and impact depth

The piecewise SEM model and corresponding path diagram for penetration showed that penetration resistance was most strongly impacted by changes in SMC, and SMC by changes in WT (Fig. 3a, Table S9). There was also a small direct negative effect of WT on penetration resistance. Spring versus autumn conditions impacted both SMC levels and penetration resistance. Furthermore, the output showed that basal cover and SMC were consistently higher in pasture fields

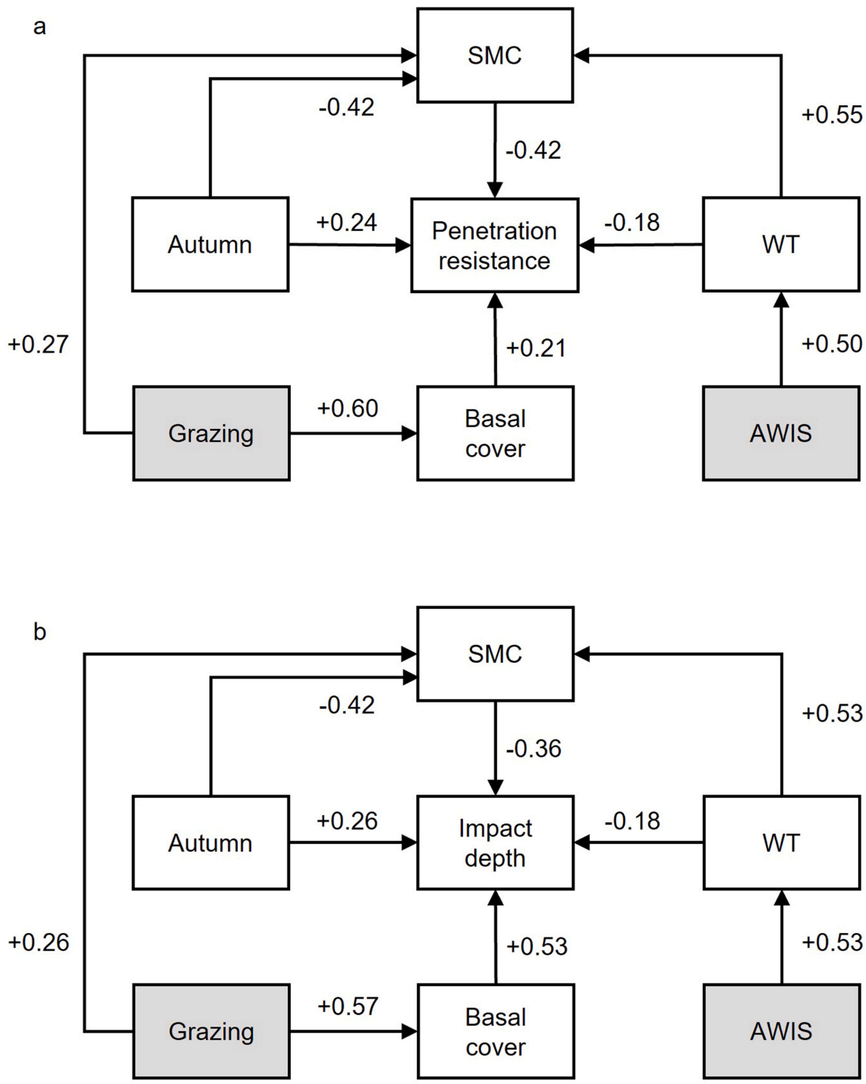

Fig. 3. Path diagram for (a) penetration resistance and (b) impact depth, based on the standardized dataset (mean = 0, standard deviation = 1). The diagram illustrates the relative strength of relationships between variables. Effects of categorical variables are shown relative to their reference category: autumn is compared to spring, and pasture fields (grazing and mowing) to silage fields (mowing only). The shaded boxes correspond to the treatment factors in the experiment: grassland use and application of an active water infiltration system (AWIS) to elevate the groundwater table on high-water fields. SMC: soil moisture content, WT: groundwater table.

compared to silage fields, and that the WT was consistently higher in high-water fields (i.e. fields in which the AWIS was installed) than in low-water fields.

The path diagram for impact depth (Fig. 3b, Table S10) was very similar to that for penetration resistance. Impact depth was most strongly affected by changes in basal cover and SMC. Basal cover had a stronger effect on impact depth than on penetration resistance.

3.3. Regression analysis – quantifying predictors of penetration resistance and impact depth

3.3.1. Penetration resistance: excluding SMC as a predictor

In the regression excluding SMC as a predictor (Model A1, Eq. 6, conditional $R^2 = 0.59$), each 1 m increase in WT resulted in a decrease in penetration resistance of 0.8 MPa in spring ($p < 0.001$), and a slightly greater decrease in autumn due to an interaction between WT and season (estimate = −0.383, $p = 0.013$) (Table S11). Under a similar WT, penetration resistance was on average 0.4 MPa higher in autumn than in spring ($p < 0.001$). Increasing basal cover by 1% resulted in an increase in penetration resistance of 0.006 MPa ($p < 0.001$). A significant interaction between basal cover and season (estimate = −0.003, $p = 0.017$) showed that the effect of basal cover on penetration resistance was smaller in autumn.

3.3.2. Penetration resistance – including SMC as a predictor

In the regression including SMC as a predictor (Model B1, Eq. 7, conditional $R^2 = 0.80$, Fig. 4), penetration resistance decreased by approximately 1.0 MPa for each m rise in groundwater table.

A 1% rise in SMC resulted in a 0.004 MPa decrease in penetration resistance (Table 3, Table S12). There was a negative interaction between SMC and season, showing that penetration resistance decreased with an additional 0.002 MPa in autumn with each 1% increase in SMC. The minor positive interaction term for SMC and WT showed that the negative effect of SMC on penetration resistance became slightly less strong at higher WT levels (Fig. 4).

Model B1 further indicated that penetration resistance was approximately 0.5 MPa higher in autumn than in spring, and showed that a higher basal cover improved penetration resistance by approximately 0.006 MPa in spring, and 0.003 MPa in autumn for each 1% increase.

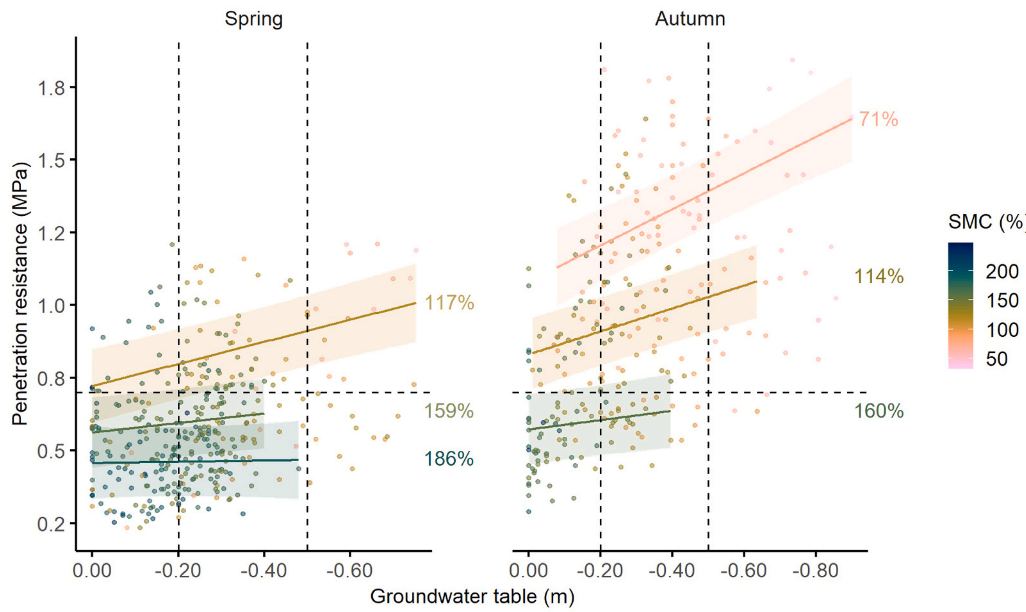

Fig. 4. Prediction plot for Model B1, showing model-based predictions of penetration resistance (MPa) across groundwater table (WT) levels (m) with 95% confidence intervals (ribbons). Lines are season-specific tertiles for SMC (0–33.3%, 33.3–66.7%, 66.7–100%), predicted at the median soil moisture content (SMC) within each tertile, and are restricted to the observed groundwater table range for a tertile. Data points represent the observed values, coloured by soil moisture content (SMC). Basal cover was held at its median value for predictions. The horizontal dashed line (0.7 MPa) indicates the threshold below which load-bearing capacity is considered inadequate to prevent sward damage from machinery or livestock. Vertical dashed lines at −0.50 m and −0.20 m mark the target groundwater tables for low- and high-water fields, respectively. See Table S13 for the SMC and groundwater table ranges and sample sizes per season-specific tertile.

Table 3
Coefficient estimates of Model B1 for penetration resistance, and Model B2 for impact depth, which included soil moisture content as a predictor. Standard deviations are shown between brackets. WT: groundwater table; SMC: soil moisture content; BC: basal cover. Significance codes: < 0.001 = '***', $0.001 < 0.01$ = '**', $0.01 < 0.05$ = '*'. See Tables S12 and S14 for full model output.

	Penetration resistance	Impact depth
(Intercept)	0.832*** (0.108)	-30.7*** (3.90)
WT	-0.990*** (0.154)	-14.2*** (3.15)
SMC	-0.00385*** (0.000448)	-0.131*** (0.0156)
Season (Autumn)	0.461*** (0.0797)	19.7*** (3.09)
BC	0.00574*** (0.000941)	0.448*** (0.0388)
WT × SMC	0.00520*** (0.00112)	*NA*
SMC × Season (Autumn)	-0.00187*** (0.000464)	0.0446*** (0.0189)
BC × Season (Autumn)	-0.00251* (0.00104)	-0.349*** (0.0435)

3.3.3. Impact depth: excluding SMC as a predictor

When excluding SMC as a predictor (Model A2, Eq. 8, conditional $R^2 = 0.59$), each m increase in WT resulted in an additional 33 mm deeper impact depth ($p < 0.001$) in spring (Table S14). In autumn, this effect was smaller due to an interaction between WT and season (estimate = 11.7, $p = 0.006$). Moreover, under a similar WT, impact depth was on average 32 mm deeper in spring than in autumn ($p < 0.001$). An increase in basal cover gave a less negative impact depth in spring (estimate = 0.451, $p < 0.001$). Due to the interaction between basal cover and season (estimate = −0.334, $p < 0.001$), this effect was weaker in autumn.

3.3.4. Impact depth: including SMC as a predictor

When including SMC as a predictor (Model B2, Eq. 9, R^2 conditional = 0.66), impact depth was found to become more negative – indicating deeper penetration – as the WT increased (Table 3, Table S15). A 1% increase in SMC led to an estimated 0.1 mm deeper penetration into the soil in spring. There was a minor positive interaction between season and SMC. Impact depth was about 20 mm less deep in autumn compared to spring, at similar WT and SMC levels. Moreover, increasing basal cover led to impact depth being less deep, with this effect again being weaker in autumn due to an interaction between basal cover and season.

4. Discussion

4.1. Load-bearing capacity in relation to WT, SMC and season

In general, an LBC of 0.6–0.8 MPa is reported as the critical range for field access without sward damage (Hamza and Anderson, 2005; Janssen et al., 2023; Scholz and Hennings, 1996; Schothorst, 1982). Our study demonstrated that raising the WT on average resulted in a decrease in LBC (measured as penetration resistance), of ~1 MPa per m elevation on this experimental farm. This translated to a decrease of 0.3 MPa when elevating the WT from −0.50 to −0.20 m. However, as penetration resistance was on average 0.5 MPa higher in autumn than in spring, this effect of an elevated WT on penetration resistance in was offset in autumn, resulting in a higher LBC in autumn compared to spring under similar WT levels. Scholz and Hennings (1996) similarly linked critical penetration resistance values for field access to groundwater depth, reporting that penetration resistance of 0.8 MPa corresponded to a groundwater level of approximately 30 cm below the soil surface. However, they did not distinguish between soil moisture levels or seasonal effects.

The SEM analysis (Fig. 3) and inclusion of SMC (and its interactions) in a regression model (Table 3), gained additional insight into the interactions between season, WT, and SMC. By combining SEM analysis with regression modelling – with inclusion and exclusion of SMC –, this study provides new insight into the interactions between WT, SMC and season in determining LBC. To our knowledge, this is the first integrated quantification of these relationships.

The analysis showed that the effect of an elevated WT on LBC can mainly be attributed to its impact on SMC, which in turn reduces LBC, which is in line with literature (e.g. Tengbeh, 1993; Angers and Caron, 1998; Bilotta et al., 2007; Holshof et al., 2011; Uusitalo and Ala-Ilomäki, 2013; Hoekstra et al., 2019; Janssen et al., 2023). Since SMC in this study was measured in the first 0.10 m of the soil, these dynamics in deeper soil layers were not captured, and it remains uncertain to what extent these layers might impact LBC. We also found a direct negative effect of WT on LBC, in addition to its impact through SMC. This relationship may be explained by soil structural changes associated with prolonged wet or dry conditions. Wet conditions reduce aggregate stability over time, by filling more pore spaces with water, weakening soil strength (Dor et al., 2019; Labancz et al., 2020), while dry conditions lead to peat shrinkage and improved aggregate stability, strengthening the soil (Schothorst, 1982).

These changes in soil structure dynamics likely also played a role in the observed seasonal difference, with LBC being higher in autumn than in spring. Prolonged wet periods, common for winter, and prolonged dry periods, as observed in summer, could influence soil structure and soil strength as explained above (Janmaat et al., 2024). Another possible explanation lies in differing drying and rewetting patterns between spring and autumn, an effect known as hysteresis (Naasz et al., 2005; Schlotzhauer and Price, 1999). In early spring, the whole soil column is typically saturated, and drying begins from the topsoil while deeper layers remain wet for longer. In contrast, in (early) autumn, the whole soil profile is generally dry, and rewetting occurs from the top down, leaving deeper layers of the soil dry for longer. In addition to soil physical processes, seasonal differences in plant development may also have contributed to the observed variation in LBC. In spring, active root growth and higher transpiration rates may strengthen the soil and promote topsoil drying, whereas in autumn reduced above- and belowground growth may minimize this effect (Patto et al., 1978; Stewart and Frank, 2008). These plant-driven processes likely interact with the drying-rewetting dynamics described above.

Prediction plots (Fig. 4) clearly showed the strong relationship between WT, season and SMC in determining LBC. In spring, LBC remained below its critical threshold of 0.7 MPa under moderate to wet conditions (i.e., the intermediate and highest SMC tertiles), largely independent of WT level. LBC exceeded 0.7 MPa under dry conditions (the lowest SMC tertile) in spring. This indicates that under wetter conditions, soil strength is already limited by moisture content itself, and variations in WT had little additional impact. The effect of an elevated WT on LBC was most distinct under relatively dry to intermediate soil moisture conditions. In autumn, LBC generally remained above 0.7 MPa and only dropped below the threshold only under wet conditions (the highest SMC tertile). Here, the effect of WT levels was greatest under wet to intermediate conditions.

It should be noted that the WT was not static but varied with varying weather conditions at our experimental location. During wet conditions (as indicated by high SMC), the actual WT was higher than the target WT, and under dry conditions (with low SMC), the actual WT was lower than the target WT. Due to these fluctuations, the difference in WT between high-water and low-water fields was smaller during wet conditions, and greater during dry conditions. The regulating properties of the AWIS system resulted in a smaller variation in response to conditions for high-water fields compared to low-water fields. The regulating capacity of AWIS depends on dynamic water level control based on real-time groundwater measurements and short-term weather forecasts, allowing drainage before heavy rainfall and enhanced infiltration during dry periods (Hoving et al., 2022). Further optimization for field operations may involve fine-tuning target groundwater levels and adapting drainage or infiltration to planned field activities, in order to balance soil bearing capacity and peat conservation (Hoving et al., 2022).

Although grazing and mowing frequency differed between fields on the experimental farm (Section 2.1), these differences were comparable across years, except in the relatively wet year 2024, when reduced LBC constrained field operations, and grazing events in particular. In that year, there was a reduction in the number of grazing days by 60 days, and the first silage cut was delayed by 16–32 days on high-water fields compared to low-water fields. In the other experimental years, there was little effect on the number of grazing days between high-water and low-water fields. This might seem to conflict with the conclusion that in spring LBC is generally always insufficient under wet circumstances, irrespective of the WT, and that WT levels become important in determining LBC under dryer conditions. However, since our developed model categorises data at the seasonal level (spring or autumn), within-season or temporal variation in SMC and LBC is not captured. In reality, SMC declined through spring, and differences between groundwater levels thus became most relevant later in the season (i.e. April and May), when SMC was relatively low. This is also the period when LBC is most critical for agricultural activities in the fields such as grazing and mowing.

Future research should further explore the relationship between key variables and LBC at smaller temporal scales, to enable the prediction of LBC in time and translate this into practical guidance on field accessibility. Given that the current study measured data on a biweekly interval, we recommend more frequent measurements during fixed periods to more accurately capture variations in conditions and enhance the practical applicability of LBC models in farm management decisions.

4.2. Grassland use and basal cover

The basal cover (used as a proxy for tiller density) was on average 65% for pasture fields and 44% for silage fields. This 21% increase in basal cover translated to a 0.1 MPa higher penetration resistance on pasture fields compared to silage fields (Model B1, Table 3). However, the difference in penetration resistance between silage and pasture fields due to a difference in basal cover was modest in comparison to the impact of SMC and WT levels. Janssen et al. (2023) also found a positive effect of sward density, measured as basal vegetation cover, on the LBC of grasslands.

Moreover, the SEM analysis revealed that SMC was generally lower on silage fields than on pasture fields. This could be related to a greater bare surface in silage fields than pasture fields due to a lower basal cover, and thus a greater amount of evaporation from bare soil. However, grassland use also impacts other parameters, such as dry matter production (which leads to higher water uptake) and sward canopy structure (Cashman et al., 2016; Jones et al., 1982), which may also affect SMC.

In general, improving basal cover or tiller density could be an important strategy to reduce the risk of sward damage, especially when penetration resistance is approaching critical levels. Strategies to increase basal cover include adjustments in grazing and mowing intensity (e.g. stocking density and duration, cutting height, stubble height) and frequency (see e.g. Cashman et al., 2016; Hoekstra et al., 2019; Holshof et al., 2011; Jones et al., 1982; van Loo, 1993; Lush and Rogers, 1992; McKenzie et al., 2006; Penning et al., 1991; Simon and Lemaire, 1987). Future research should quantify how different grassland-use strategies can influence and possibly further increase LBC and field accessibility (see also impact depth, below).

4.3. Impact depth versus penetration resistance

Consistent with our hypothesis, we found that impact depth was more sensitive to changes in basal vegetation cover (Fig. 3) compared to penetration resistance. This is in contrast with Janssen et al. (2023), who found that penetration resistance was more sensitive to changes in basal cover compared to impact depth. However, in their study, fields with a wide range of soil, management and vegetation characteristics were measured. We found that both penetration resistance and impact depth responded less to changes in basal cover in autumn compared to spring. In other words, increased basal cover had less impact on LBC in autumn, irrespective of the method used for measuring LBC. This might be caused by SMC playing a more important role in spring, when soils are generally wetter, thus again linking to soil structure dynamics.

Moreover, at low penetration resistance, impact depth increased sharply in response to small increases in penetration resistance

(Figure S3). Given that penetration resistance is typically low at high SMC, this indicates that impact depth is particularly more sensitive under relatively wet conditions. This may suggest that differences in LBC under relatively wet conditions and as affected by difference in sward density are better captured when using a method with a larger impact surface (resembling a cow hoof) as opposed to the 500 mm^2 conus used for measuring penetration resistance.

In contrast to penetration resistance, impact depth was not influenced by an interaction between WT and SMC and remained equally sensitive over WT levels and moisture conditions. Moreover, while penetration resistance plateaued under wetter conditions, impact depth did not show such a plateau, further supporting our hypothesis that impact depth is more sensitive under relatively wet conditions.

Based on the threshold value for penetration resistance, a threshold of −15 mm for impact depth was derived from their exponential relationship (Figure S3). Our found threshold differs slightly from the threshold value for impact depth of −18 mm as determined by Janssen et al. (2023). In our study, hoof depressions deeper than 15 mm can be regarded as indicative of potential sward damage. While there is limited literature available on threshold values for poaching it is acknowledged that the top 50 mm of the soil is most critical for poaching damage (Bilotta et al., 2007; Vzzotto et al., 2000).

Further research to establish a threshold value for impact depth should be conducted under varying conditions to ensure the threshold is supported by a robust and representative dataset. This is particularly important as a threshold value in millimetres is more tangible and intuitive for farmers than a threshold value in MPa (Janssen et al., 2023).

4.4. Broader application and implications

The necessity of rewetting peatlands to minimize CO_2 emissions is evident in the face of climate change (Evans et al., 2021; Piayda et al., 2020; Schrier-Uijl et al., 2014; van de Riet et al., 2013). Altogether, our findings indicate that it is essential to consider the different seasonal patterns and changing moisture conditions over time to reduce the risk of sward damage on agricultural peatlands with a raised WT. While the impact of raised (surface) water tables on LBC has been a subject of research (see e.g. Beuving et al., 1989; Holshof et al., 2011; Janmaat et al., 2024; Schothorst, 1982), to the best of our knowledge, this is the first time the relationship between LBC (measured as both penetration resistance and impact depth), WT and underlying factors has been quantified and modelled in an integrated manner. Further expansion of this research could help refine models that assess the financial impacts of a raised WT, as shown in previous work (e.g., de Vos et al., 2006; de Vos, 2010; Poppe et al., 2021). This could, in turn, contribute to the design of compensation schemes or other supportive measures to encourage farmers to raise groundwater levels in their fields.

While our findings are based on data from fields on a single experimental farm, in general peatlands vary greatly in physical, chemical, and hydrological properties, such as bulk density and peat thickness, (Jansen et al., 2000; Kazemian et al., 2011; Montanarella et al., 2006; Piayda et al., 2020). Likewise, drainage and infiltration systems determine groundwater dynamics and variation in SMC and soil strength. The patterns we observed are therefore likely intertwined with the specific peat properties and groundwater management of the experimental site. Future studies should evaluate the applicability of our findings across peatlands differing in soil composition and drainage systems.

Furthermore, the inclusion of other farming systems should be considered. Our study focused on LBC in relation to optimizing grassland use and productivity, and the use of AWIS is considered particularly suitable for intensive dairy-farming systems (Jansen et al., 2009; van den Born et al., 2016; Wils et al., 2025). Particularly, AWIS can slow peat oxidation while minimally impacting grass yield (Hoving et al., 2024, 2009; van Dijk et al., 2026). Previous studies on subsoil irrigation have shown reductions in peat decomposition and CO_2 emissions, but also shown that the effectiveness depends strongly on, among others, weather conditions (Boonman et al., 2022). Moreover, such drainage systems contribute little to restoring biodiversity (Heuts et al., 2024; van der Laan et al., 2025), and will not stop peat oxidation completely (Wils et al., 2025). Lastly, rewetting through water infiltration systems can have great impact on water demands, particularly during dry periods (Hoving et al., 2020; Jansen and Querner, 2010; Rozemeijer et al., 2019); may increase phosphorous losses to surface water (de Vos et al., 2006; van de Riet et al., 2013; van Dijk et al., 2026); and may reduce the abundance of soil life such as nematodes and earthworms (van der Laan et al., 2025).

While measures like AWIS can help maintain current dairy-farming practices on rewetted peatlands, ensuring long-term resilience of peatland agriculture also requires exploring alternative strategies for farming under impeded LBC. These include technical adaptations, such as the use of adjusted machinery to reduce soil disturbance (Schröder et al., 2015). At a system level, management and land-use strategies such as integration of nature management, extensification, or the development of business models for paludiculture warrant further investigation. In addition, farming on rewetted peatlands may require reconsideration of management operations, for example by aligning the timing and intensity of grazing with elevated groundwater levels to reduce soil disturbance and compaction risks (Donkor et al., 2002; Hoekstra et al., 2019; Mapfumo et al., 1999). These approaches may create more space for nature and non-agricultural ecosystem services, such as biodiversity conservation (Bufe et al., 2024; Deru, 2021; Heuts et al., 2024; Liu et al., 2023; Schrier-Uijl et al., 2014; Wils et al., 2025).

5. Conclusion

This study demonstrated that the load-bearing capacity (LBC), measured as penetration resistance, decreased on average by 1 MPa per m elevation in groundwater table (WT) at the studied experimental farm using AWIS. As a result, an elevated WT increased the likelihood of insufficient penetration resistance (< 0.7 MPa). The reduction in LBC under a raised WT was mainly through its effect on soil moisture content (SMC, 0–0.10 m) and was strongly dependent on season. Understanding this strong interplay between moisture conditions, seasonal variation, and WT in determining LBC and accessibility of agricultural peatlands is essential in predicting field accessibility and assessing the financial impacts of a raised WT for farmers. We found that increasing basal cover through grazing had a modest positive effect on LBC, mitigating the reduction in LBC on average by 0.1 MPa compared to fields that were only mown, which can be valuable around threshold levels of LBC. Moreover, this study underscores the value of the cow-hoof method as a complementary tool to measure LBC, as impact depth was particularly sensitive under wet conditions and reflected how changes in sward characteristics, influenced by grassland use, can affect LBC. The strength of found relationships is influenced by site-specific peat properties and drainage system and should be interpreted within this context. Future research should focus on more frequent data collection and include a wider range of soil types, geographic contexts, and farm management systems to enhance predictive capacity and applicability of tools that can predict LBC in time. This can help inform field management decisions and compensation schemes to support a wide range of farmers to successfully farm under raised WT conditions.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used OpenAI - ChatGTP [https://chat.openai.com/] to improve readability of the text and to assist in writing code for R. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

M. Jongbloed: Methodology, Investigation, Writing – original draft, Writing – review & editing. **N.J. Hoekstra:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **J.C.J. Groot:** Methodology, Writing – review & editing. **M. van den Hout:** Methodology, Investigation, Writing – review & editing. **I.E. Hoving:** Methodology, Writing – review & editing. **P.W.L. Janssen:** Methodology, Writing – review & editing. **N. van Eekeren:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2026.107186.

Data availability

Data will be made available on request.

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