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Higher density swards have a higher load bearing capacity

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Abstract

Increasing the water table is an important pathway to reduce greenhouse gas emissions from peaty soils. In order to continue utilizing grasslands on these soils, methods to increase load bearing capacity at a higher water table are sought. The objective of this study was to assess the effect of sward density on load bearing capacity, measured as both penetration resistance and the newly developed method measuring load bearing capacity through impact depth. Simultaneously, a new method to measure load bearing capacity through impact depth was developed. The study was conducted between 2018 and 2020 on 14 different farms in the western peat meadow district in the Netherlands, where the sward density measured with the point quadrat method ranged from 24% to 92%. Swards with a higher sward density showed a higher load bearing capacity than swards with a lower density. In a modelling approach an increase from 30% sward density to 90% sward density could result in a lengthening of the grazing season between three (11%) and six weeks (22%), depending on the soil moisture conditions. Load bearing capacity was also highly correlated with gravimetric soil moisture content as wetter conditions lowered load bearing capacity. In order to capture load bearing capacity more accurately a new measurement device was constructed which represents treading cattle. Both output (impact depth) and method (resembles cow hoof) are close to practice, which makes it a very suitable method allowing for easy interpretation by farmers.

KEYWORDS

grazing, impact depth, *Lolium perenne*, meadow, peat, penetration resistance

1 | INTRODUCTION

To facilitate agricultural production, peaty soils have been drained for improving plant production and improving load bearing capacity for grazing and access of the land by machinery for fertilization and harvesting (Schothorst, 1982). This drainage leads to oxidation of the peat soils, causing decomposition of the organic matter, greenhouse gas (GHG) emissions and soil subsidence (Armentano, 1980; Kasimir-Klemedtsson et al., 1997; Van den Akker et al., 2010). Although these soils represent only 0.3% of the global land area, they contribute to 6% of the total anthropogenic CO_2 emission (Joosten, 2011). Agricultural land use accounts for 14% of the surface of peat soil in Europe, with the majority of these consisting of pastures and meadows (Joosten & Clarke, 2002). One method through which the peat oxidation and emissions of these drained peat soils can be reduced is through raising the ground water level again (Hendriks et al., 2008; Querner et al., 2012). However, the economic viability of agricultural operations is affected by an increase in the ground water table through a decrease in plant production and problems with the utilization of pastures through a lower load bearing capacity (De Vos et al., 2010; Schothorst, 1961). According to Hoekstra et al. (2019) load bearing capacity is already limiting the grazing season in some years. An increase in the ground water table will increase the importance of load bearing capacity for utilization of grass through grazing.

Peat soils differ from mineral soils in moisture content and permeability (Huat et al., 2019). When the load bearing capacity is not adequate, accessing the land with machinery or livestock will result in damage to soil structure and sward composition (Scholefield & Hall, 1986; Schothorst, 1961). Damaged places are more susceptible to weed infestation (Morris & Reich, 2013) and have a lower yield through direct effect on harvestable matter. Moreover, soil compaction, poaching and pugging can lead to higher emissions of N_2O through a disturbed water management (García-Marco et al., 2014; Snyder et al., 2009). Understanding the aspects which determine the load bearing capacity is essential if the water table is raised and an adequate load bearing capacity is to be maintained.

The load bearing capacity of peat soils is influenced through different mechanisms. The primary pathway is through soil moisture content (SMC) (Uusitalo & Ala-Ilomäki, 2013). An increase in SMC reduces the shear strength of these soils. Historically, the moments when load bearing capacity is limiting are during spring and autumn (Patto et al., 1978). Due to rainfall and lower evapotranspiration, the ground water level is higher, and the SMC is higher. The second pathway is through the physical properties of the soil such as mineral or organic matter content. Soils high in organic matter may result in a low shear strength due to a high retained water capacity (Patto et al., 1978). Furthermore, the organic matter origin of the peaty soil has an influence on how it behaves in relation to water retention (Heiskanen, 1993). The third pathway is through the sward and the density of grass. Research has shown that vegetation contributes to the load bearing capacity through aboveground plant matter, belowground plant matter (e.g., roots), and indirectly through the formation of water stable aggregates (Bilotta et al., 2007; Patto et al., 1978). Climo and Richardson (1984) reported that pastures with more productive species such as perennial ryegrass and white clover tend to have a lower load bearing capacity than pastures with nutrient poor grassland swards. In contrast, Deru et al. (2018) measured a higher load bearing capacity in productive dairy grasslands than in semi-natural grasslands on peat soil. Higher sward densities due to grazing in productive pastures on peat soils have also been shown to increase load bearing capacity (Hoekstra et al., 2019). The effect of sward density on load bearing capacity is most likely through a combination of increased root density and a higher number of plants or tillers in the top soil, creating a stronger sward.

Historically, penetration resistance has been measured on relatively small surface areas. A 5 cm^2 surface conus is pressed through the sward using a penetrometer. The penetration resistance is expressed in kilopascal (kPa). The penetration resistance threshold value for grazing cattle has been determined at 700–800 kPa (Hamza & Anderson, 2005; Wind & Schothorst, 1963). Grazing below this threshold will result in significant damage to sward and soil. However, due to the small contact area this device does not adequately represent treading cattle (Scholefield & Hall, 1986). We developed a device based on the fall-cone principle of Bradford and Grossman (1982), which represents the hooves of treading cattle.

Historically ('60 and '70 of last century), research regarding penetration resistance and SMC was focussed on the lowering of the groundwater table. The recent interest in raising the ground water table again puts the research regarding load bearing capacity back on the agenda. To our knowledge, no study on the exact role of sward density on load bearing capacity has been performed so far. In this study we measured the load bearing capacity in relation to the sward density, SMC and other soil characteristics in the western peat area of the Netherlands in fields with low, average and high load bearing capacities as regarded by farmers. We aimed at capturing the role of (i) the sward density in relation to load bearing capacity under different SMC conditions and (ii) to improve methods to measure load bearing capacity. Our hypotheses were that (i) a higher sward density will increase load bearing capacity, and (ii) that the newly developed method of measuring impact depth is more sensitive in low load bearing conditions in general and to changes in sward density specifically.

2 | MATERIALS AND METHODS

2.1 | Set-up

The study was carried out on drained peat soils (Terric Histosols; FAO, 2015) in the western peat region in the Netherlands in the Krimpenerwaard polder. In 2018, 24 fields were measured during 1 week, between April 10th and 17th. To get a wide range of load bearing conditions on each farm two fields were chosen based on the experience of the farmer, choosing an average field and an extreme field. An average field was a field that was considered comparable to most fields within the farm in terms of load bearing capacity. An extreme field was a field that had above average low or high load bearing capacity according to the farmer. Botanical analysis show that the fields contained on average 60% *Lollium perenne* and 19% *Poa trivialis* canopy cover. The other species consisted of different grasses, legumes and forbs, but which differed between fields. In 2019 and 2020, measurements in eight fields were carried out at weekly intervals in a subset of the fields measured in 2018. These eight fields were chosen based on creating a wide range of sward densities, grazing vs mowing and soil characteristics. Four fields measured in 2019 were replaced with four other fields in 2020. This decision was made in order to compare fields within a similar farming system. Measuring took place from the 1st week of March through to the 2nd week of April, as the first manure application and the first grazing of the year usually take place during this period. The fields on which measurements were conducted showed a wide range of soils characteristics, management and sward densities (Table 1). Organic matter content in the measured soils ranged from 27% to 60%. Some fields were grazed and some were mowed only. The grazing density ranged from 1.7 cows ha^{-1} to 7 cows ha^{-1}. All were fertilized using cattle slurry, and most received additional artificial fertilizer. The data from 2019 and 2020 was used to describe the course of penetration resistance, impact depth and moisture content during the spring.

2.2 | Soil measurements

In each field a permanent plot of 10 m by 10 m was marked with iron plates and GPS. In these plots 20 soil cores per plot were taken with a grassland auger (Eijkelkamp, 0–10 cm) to determine the gravimetric soil moisture content (SMC, g water g^{-1} dry soil) at each measurement occasion. The soil was dried at 105°C for 24 h. Additional samples taken in the 1st week of sampling were analysed. Clay (<2 μm diameter) content was determined through density fractionation (NEN 5753, 2018). Silt (2–50 μm) and sand (>50 μm) were determined by the pipette method and sieving (fractions 2, 16, 50, 63, 125, 180, 250, 355, 500, 1000 and 2000 μm). Organic matter content was determined by loss-on-ignition (NEN 5754, 2014). Penetration resistance of soils was measured using a penetrometer (Eijkelkamp, The Netherlands) with a come diameter of 5 cm^2 and an apex angle of 60°. A total of 15 measurements were taken per plot and expressed as the average value of the maximum force needed to push the cone through the sod. The threshold that is generally regarded using the penetration resistance is 700–800 kPa(Hamza & Anderson, 2005; Wind & Schothorst, 1963).

The penetrometer only determines the penetration resistance on a small surface area (5 cm^2), a new measurement device was constructed in order to better assess the impact of grazing cows on the sod. A penetrometer exerting a force through a hoof was already constructed by Scholefield and Hall (1986). This machine was not suitable for the purpose of this research because of its size and limited portability. Inspired on the Swedish fall-cone device (Bradford & Grossman, 1982), a device that would provide the right amount of force on the soil and is easy to handle, a falling weight was developed. The contact surface of the hooves of cows range from 15.0 to 50.0 cm^2 (Van der Tol et al., 2003). The pressure exerted by trading livestock is between 50 and 80 Newton (N) cm^{-1} with a maximum of up to 200 N cm^{-1} (Van der Tol et al., 2003). Based on the formula of force of a falling object, the surface of the hooves and the pressure of treading cattle, a cylindrical weight of 8 kg with a diameter of 68 mm was dropped from a height of 0.6 m. The surface of this weight was 36.3 cm^2, which was in the range of Van der Tol et al. (2003). Combining these parameters the exerted pressure is 64.9 N cm^{-1} when the distance travelled after impact is 0.02 m. The impact of the weight in the soil was measured in cm from the original soil surface with an accuracy of 0.5 cm. The exact level of force exerted by the falling weight is dependent on the impact depth. The formula how the amount of Newton is calculated:

$$N = \frac{mgh}{d}$$

In which: N = Average impact force in Newton; m = mass of object in kg; g = gravity constant of 9.81 m s^{-2}; h = height from which mass is released in m; d = distance travelled after impact in m.

This measurement was conducted 10 times per plot.

TABLE 1 Average, minimal and maximum soil characteristics and sward density for measured fields (2018–2020)

	Average	Minimum	Maximum
Soil organic matter (%)	44.1	26.9	59.4
Clay (%)	25.6	11.0	40.0
Silt (%)	15.7	10.0	30.0
Sand (%)	12.2	2.0	27.0
Sward density (%)	58.0	24.4	92.2

2.3 | Sward density

Sward density was measured using the point quadrat method (Levy & Madden, 1933). Ten spokes in a row at 10 cm were placed through a

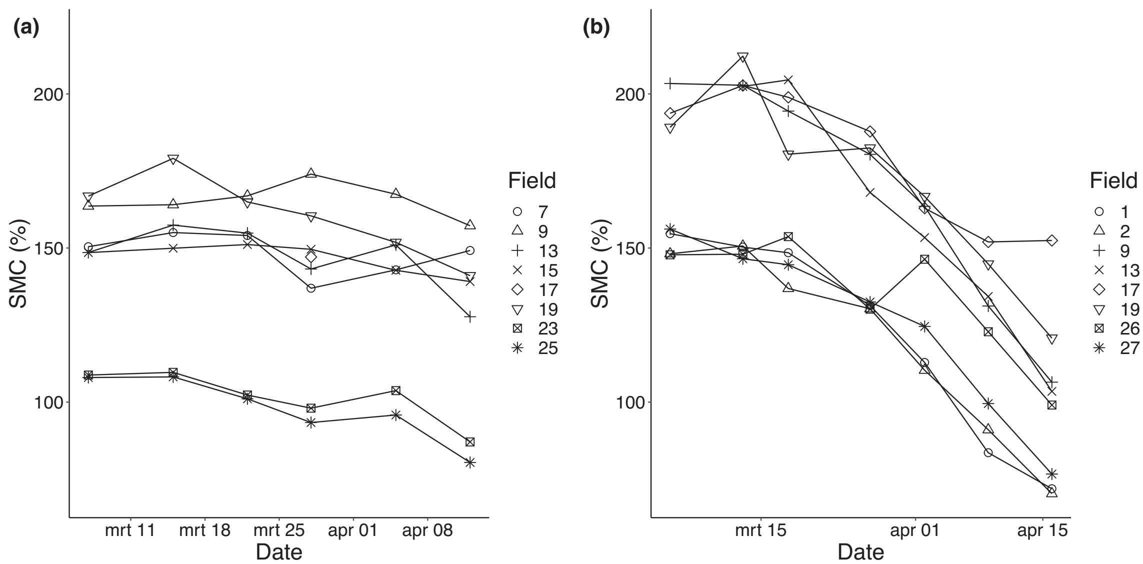

FIGURE 1 Development of SMC (%) in soil measured in the different fields throughout the spring in 2019 (a) and 2020 (b)

PVC tube. The spokes touching the bare soil surface or litter, and did not touch the base of a grass tiller were counted as soil. Spokes touching the base of a grass tiller (as opposed to litter or bare soil) at the soil surface was recorded as sward. This measurement was repeated 10 times per plot, and the grass sward density was calculated as a percentage. The cover recorded on soil level was regarded as sward density (Spedding & Large, 1957; Whalley & Hardy, 2000).

2.4 | Weather conditions

Monthly temperature and rainfall data were collected at a nearby rainfall station (Gouda) (KNMI, 2021b) and a nearby weather station (Cabauw) (KNMI, 2021a). In 2018, the spring was wet compared to the long-term average. In 2019, the spring was considered relatively dry and in 2020 the spring started relatively wet and became relatively dry after March (Appendix S1). Average monthly temperatures in all 3 years were close to the long term average (Appendix S2).

2.5 | Statistical analysis

All data were analysed using R version 4.2.1 (R Core Team, 2022). Pearson correlations were carried out to assess correlations between soil parameters. Multiple linear regression was performed with penetration resistance and impact depth as dependent variables. Backwards selection was used for selection of independent variables. For both models the independent variables were moisture content, sward density and soil organic matter. Models were tested for interactions. The models were applied to assess and visualize the effect of sward density (range between 30% and 90% in 20% intervals) during the 2019 and 2020 using an average organic matter content of 44.1% and

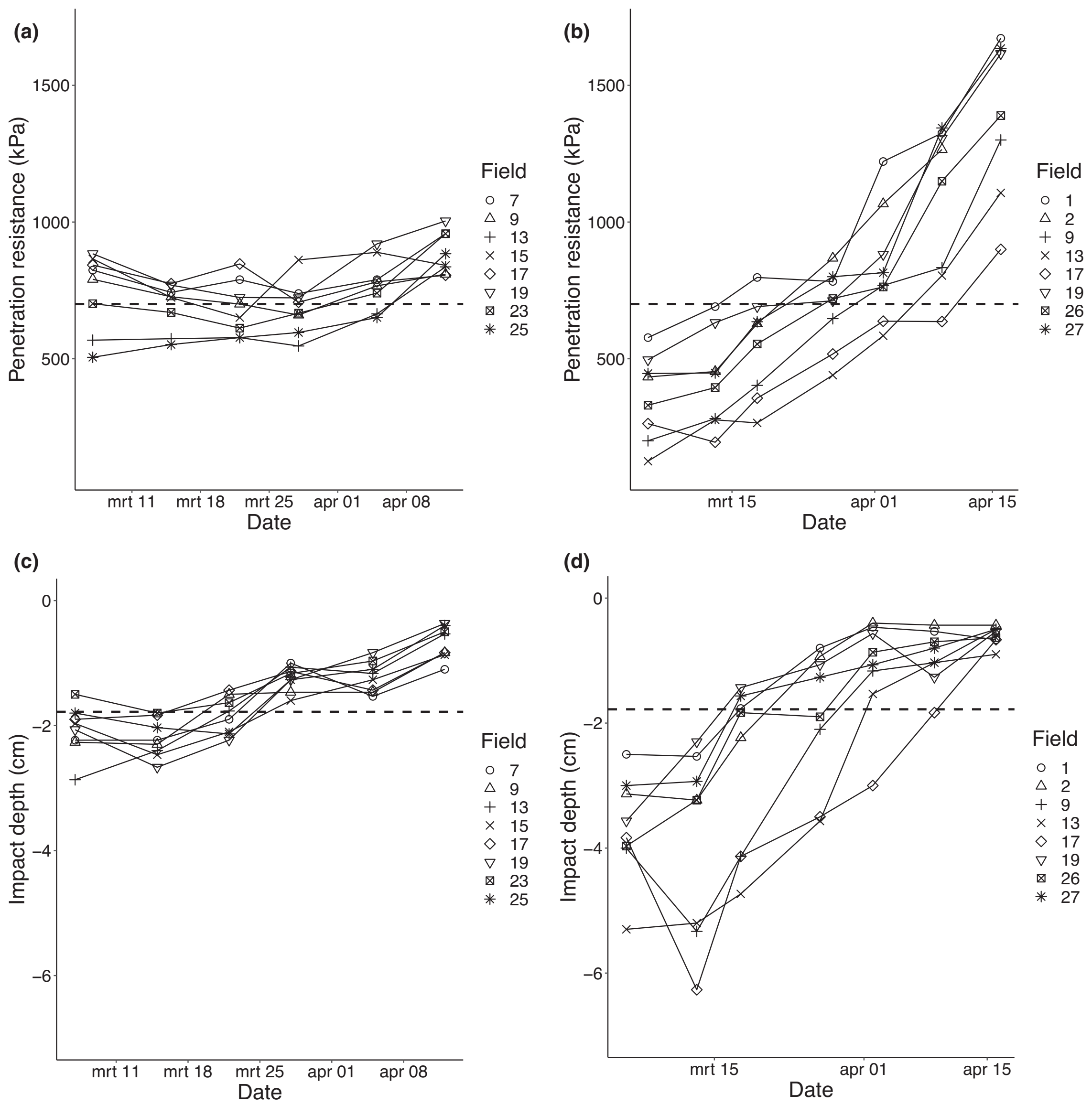

FIGURE 2 Development of penetration resistance in (a) 2019 and (b) 2020, and impact depth in (c) 2019 and (d) 2020. The threshold for grazing is indicated by the dashed black line (700 kPa for penetration resistance and −1.8 cm for impact depth (see Paragraph 3.3))

actual average soil weekly moisture content. The data on which the models are based excluded values higher than 1200 kPa for penetration resistance and values lower than 4 cm impact depth, as between these values there was a linear relationship between penetration resistance and impact depth. Outside of this range the relationship became more exponential and was therefore not suited to the model.

3 | RESULTS

3.1 | Soil moisture content, penetration resistance and impact depth in spring 2019 and 2020

SMC was relatively constant throughout the measurement period of 2019 but decreased rapidly from wet to dry in the measurement period of 2020 (Figure 1a,b). Clear groups can be observed in SMC based on organic matter content, as the fields with a lower organic matter (Fields 23 and 25 in 2019; Fields 1, 2, 26 and 27 in 2020) content also had a lower SMC. The penetration resistance in the 1st measurement week of 2019 was below the threshold for grazing for two out of the eight fields measured (Figure 2a). In 2020 at the start of the measurement period, all eight fields had a penetration resistance lower than this threshold (Figure 2b). In 2019 the measured penetration resistance hovered around the threshold value of 700 kPa for some weeks while in 2020 the changes were more rapid. The impact depth showed a similar pattern as the SMC (Figure 2c,d). In spring 2019, the impact depth ranged from 0.4 to 2.9 cm, whereas in 2020 the impact depth ranged from 0.4 to 6.3 cm.

3.2 | Relationship between load bearing capacity, sward density and soil properties

The SMC was significantly correlated to both the penetration resistance of the soil and the impact depth (Table 2). The relationship between SMC and penetration resistance ($r = -0.61$, $p < .001$) (Figure 3a) was comparable to the relationship between SMC and impact depth ($r = -0.59$, $p < .001$) (Figure 3b). There was a significant positive correlation between sward density and penetration resistance ($r = 0.53$, $p < .001$) and between sward density and impact depth ($r = 0.38$,

TABLE 2 Correlation table load bearing capacity (penetration resistance and impact depth) with SMC, sward density, SOM and soil texture

	Penetration resistance	Impact depth	Sward density	SMC	SOM	Silt	Sand
Impact depth	**0.78*** **						
Sward density	**0.53*** **	**0.38*** **					
SMC	**−0.61*** **	**−0.59*** **	**−0.18* **				
SOM	0.01	−0.09	−0.03	**0.59*** **			
Silt	−0.13	−0.03	**−0.28** **	−0.14	**−0.28** **		
Sand	−0.02	−0.09	**0.28** **	**−0.19* **	**−0.60*** **	**−0.24** **	
Clay	0.08	**0.18* **	0.04	**−0.65*** **	**−0.83*** **	−0.06	**0.32*** **

Note: *p* values: ***<.001; **<.01; *<.05; .<.1. Significant correlations written in bold.

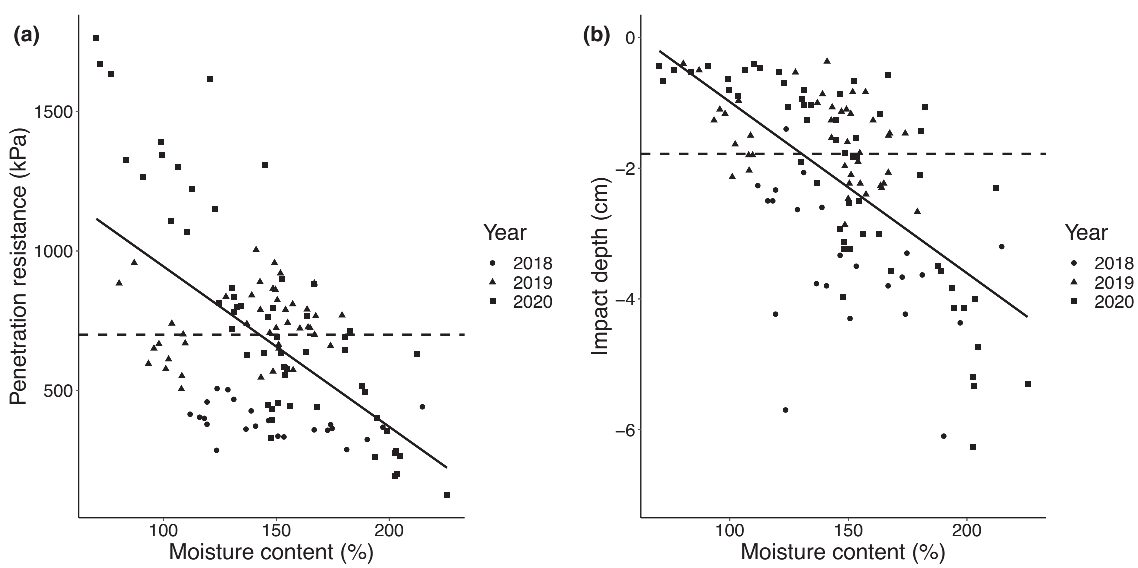

FIGURE 3 (a) Correlation between SMC and load bearing capacity (kPa) ($r = -0.61$. $p < .001$). Added dashed line represents threshold value at 700 kPa. (b) Correlation between SMC and impact depth (cm) ($r = -0.59$. $p < .001$). Added dashed line represents threshold value at −1.8 cm.

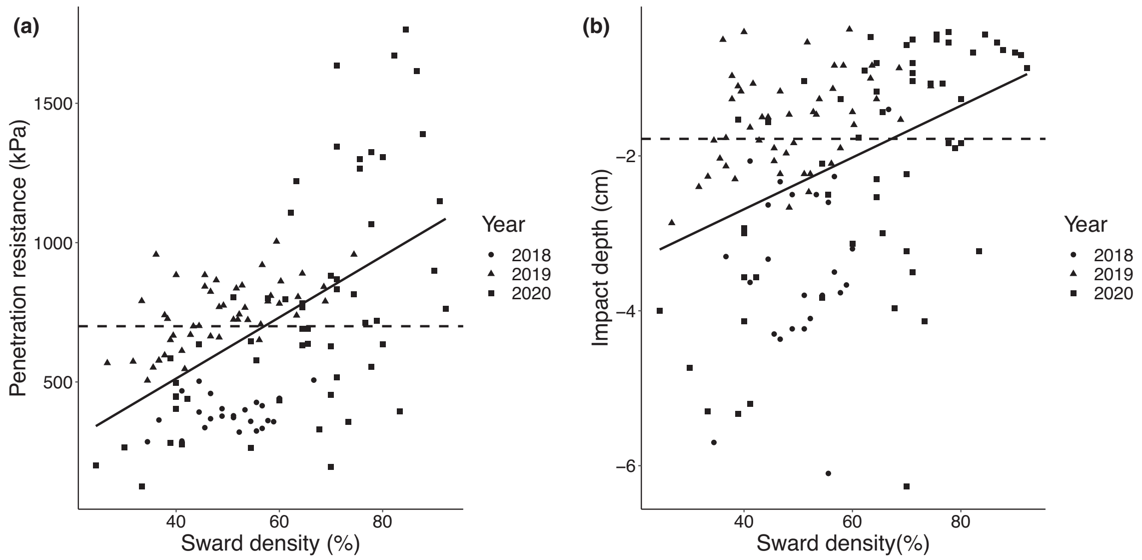

FIGURE 4 (a) Correlation between sward density (%) and load bearing capacity (kPa) ($r = 0.53$. $p < .001$). Added dashed line represents threshold value at 700 kPa. (b) Correlation between sward density (%) and impact depth (cm) ($r = 0.38$. $p < .001$). Added dashed line represents threshold value at −1.8 cm.

$p < .001$) (Figure 4a,b). Furthermore, there was a significant negative correlation between SMC and sward density ($r = -0.18$, $p < .05$).

Soil organic matter content was negatively correlated with sand ($p < .001$), silt ($p < .01$), and clay ($p < .001$). Although soil organic matter content was highly correlated with the SMC ($p < .001$, Table 2), no significant correlation between the soil organic matter content and the penetration resistance or the impact depth was found.

3.3 | Impact depth and penetration resistance for measuring load bearing capacity

There was a strong correlation between penetration resistance and impact depth ($r = 0.82$, $p < .001$, Table 2, Figure 5). Based on the threshold value for grazing of 700 kPa for penetration resistance we estimated the threshold value for grazing of the impact depth at −1.8 cm.

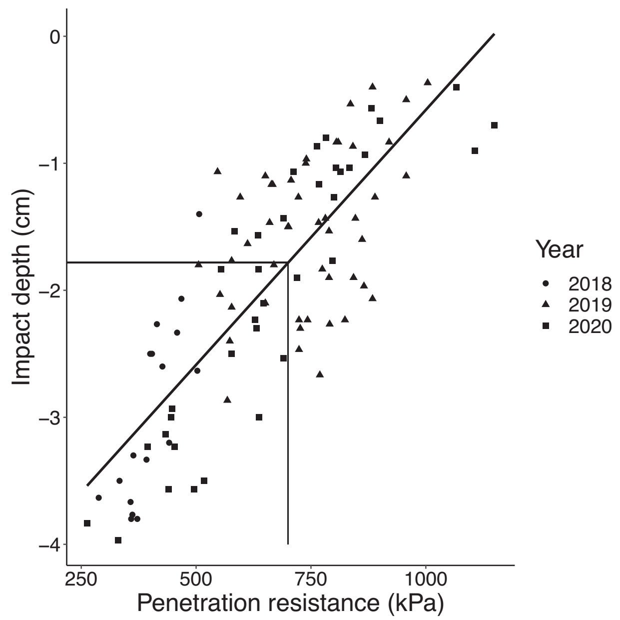

FIGURE 5 Relationship between penetration resistance and impact depth ($r = 0.82$, $p < .001$). Black horizontal and vertical lines represent threshold values for penetration resistance (700 kPa) and impact depth (1.8 cm)

3.4 | Model predicting penetration resistance and impact depth

Using a stepwise regression approach we developed models predicting the penetration resistance and the impact depth as a function of SMC, sward density and soil organic matter (Table 4). The adjusted R^2 was 0.53 and 0.50 for the model describing penetration resistance and impact depth, respectively.

We applied the model to assess the effect of sward density on load bearing capacity during 2019 and 2020. Penetration resistance increased by 343 kPa for an increase in sward density from 30% to 90% (Figure 6a,b). The model was applied to assess the effect of sward density on the load bearing capacity under prevailing soil moisture conditions in 2019 and 2020 under average soil organic matter content. For the average field in the studied area an increase in sward density (from 30% to 90%) could advance the period, in which grazing would be possible without damage to the sward, with 6 weeks in 2019 and 3 weeks in 2020 (Figure 6a–d).

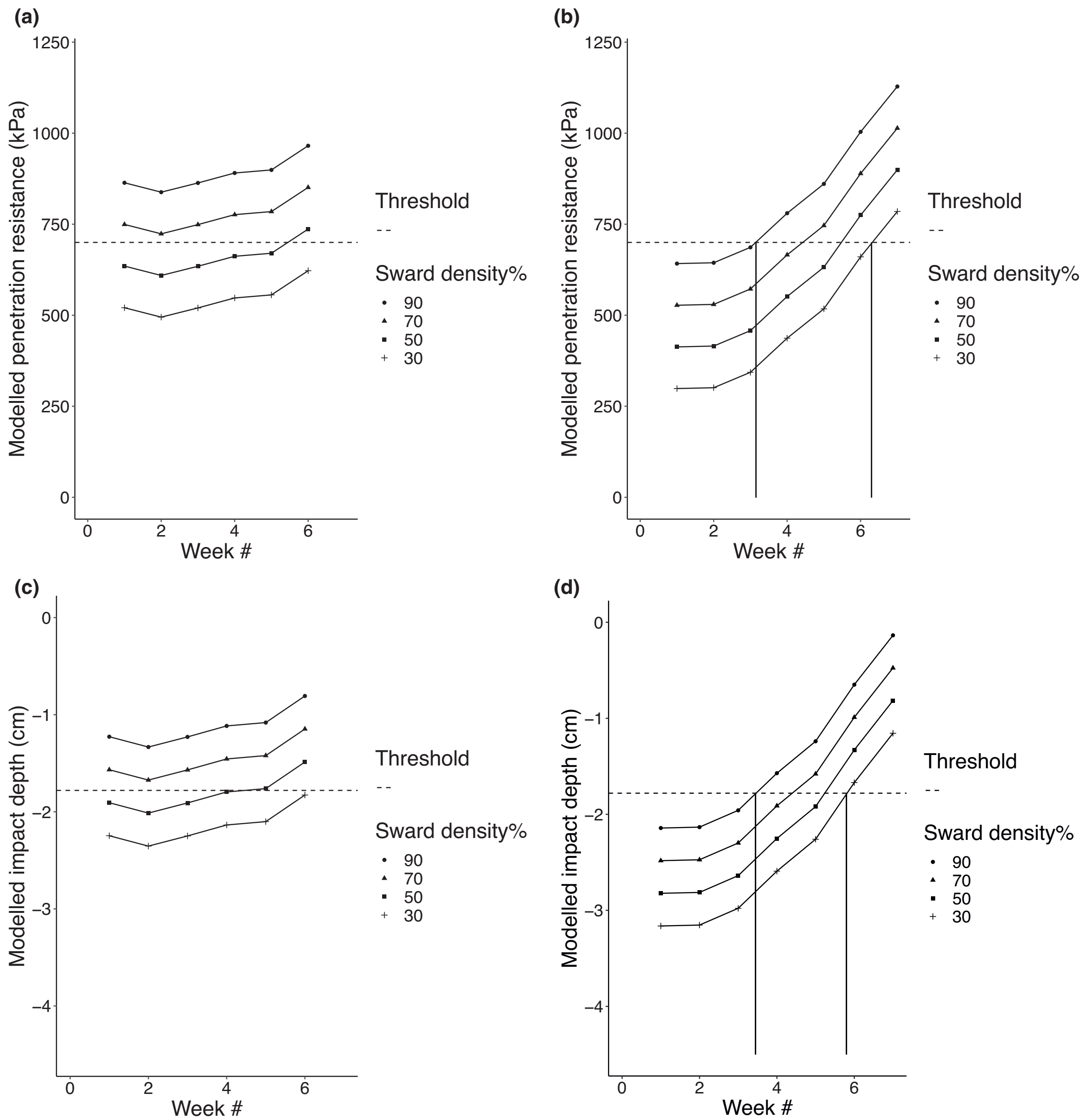

FIGURE 6 Modelled penetration resistance for 2019 (a) and 2020 (b) and modelled impact depth for 2019 (c) and 2020 (d). Threshold for grazing without damage to sward is noted in dotted line. Vertical solid black lines indicate moments at which highest (90%) and lowest (30%) sward density reach threshold for grazing in 2020

4 | DISCUSSION

4.1 | Sward density improves load bearing capacity

In line with our hypothesis, a higher sward density improved the load bearing capacity as indicated by penetration resistance and impact depth (at equal SMC and soil texture), in line with other studies (Bilotta et al., 2007; Patto et al., 1978; Stoepker, 1969; Wallenburg, 1969). A higher tiller density creates a denser sward structure which can improve load bearing capacity. More tillers per unit ground area decrease the chance of direct hoof-soil contact, and therefore decrease the chance for damage through treading. Sward density can influence load bearing capacity indirectly through a higher root density (Bilotta et al., 2007). Rooting density was outside of the scope of this research, but Deinum (1985) has shown that tiller density and root density are positively correlated.

4.2 | Impact of SMC and soil texture

SMC is the most important factor determining the load bearing capacity. There was a high level of correlation between SMC and load bearing capacity measured as penetration resistance and impact depth. Moreover, SMC was highly significant in both models (Table 3). A higher moisture content results in more pore space being filled with water (Bilotta et al., 2007; Climo & Richardson, 1984; Mullins &

Fraser, 1980; Uusitalo et al., 2015; Uusitalo & Ala-Ilomäki, 2013). This reduces the internal friction in the soil and thus reduces soil strength (Bilotta et al., 2007). Moisture content is the most important driver of the development of the load bearing capacity in spring. Grass growth and higher temperatures increase evaporation of soil moisture, and this results in an increase in penetration resistance and a decrease in impact depth (Hoekstra et al., 2019). As an increased sward and tiller density enhances evapotranspiration, this may also explain the significant negative correlation between SMC and sward density.

One of the surprising aspects of the model was the positive effect of SOM on load bearing capacity. From literature, this relationship is mostly negative (Lima et al., 2015; Pereira et al., 2007). A possible explanation for this could be the nature of gravimetric moisture determination. Soils with a lower SOM content, which have a lower soil bulk density, have a lower volumetric moisture content compared to soils with a higher SOM content at the same gravimetric moisture content (Evett, 2008; Rawls et al., 2003; Schothorst, 1963). Therefore, in future studies volumetric moisture content determination could be more suited in relation to soil strength measurements. Therefore, the positive effect of SOM on load bearing capacity in the models can be interpreted as a correction for the use of gravimetric moisture content (as opposed to volumetric).

4.3 | Penetration resistance versus impact depth

In contrast to our hypothesis, penetration resistance was more sensitive to changes in sward density compared with impact depth ($r = 0.53$ and 0.38, respectively, Table 2). The larger measurement surface of the impact depth potentially could increase sensitivity but this was not the case in this study. Penetration resistance and impact depth were equally sensitive to changes in SMC, which was not in line with our hypothesis. ($r = -0.61$ and -0.59, respectively, Table 2). A possible explanation for this would be the accuracy of the impact depth. This was measured at 0.5 cm intervals, while a higher accuracy might be necessary. Also, penetration resistance was measured 15 times per plot while impact depth was only measured 10 times. Despite the higher level of correlation of SMC with penetration resistance compared to impact depth, this did not translate into higher percentages of variation explained in the models.

There was a high level of correlation between penetration resistance and impact depth ($r = 0.78$, Table 2). Based on this linear correlation we have determined the threshold value of impact depth at −1.8 cm (Figure 5). A threshold value for impact depth is an important aspect when translating values to grazing by cattle. The threshold value of penetration resistance is difficult to translate to practical situations with dairy farmers. The impact depth is a method of visualizing load bearing capacity to farmers as both the method (resembles cow hoof) and the output (depth of the footprints) are close to practice, while also accurately resembling load bearing capacity. At the same time this newly developed method of impact depth is suitable for usage in field and is easy to transport, unlike methods like the method created by (Di et al., 2001).

TABLE 3 Regression results penetration resistance and impact depth

	Penetration resistance	Impact depth
Constant	562.40*** (93.87)	−1.135 (0.475)
SMC	−6.30*** (0.65)	−0.026*** (0.003)
Sward density	5.72*** (0.98)	0.017*** (0.005)
SOM	15.46*** (2.07)	0.047*** (0.010)
R^2	0.54	0.49
Adjusted R^2	0.53	0.50
Number of observations	111	109
RMSE	147.75	0.719
F statistic	42.17	35.70

Note: Significance is noted through: *<.05; **<.01; ***<.001. Standard errors are displayed in brackets.

4.4 | Practical implications

The modelled influence of sward density on a field resulted in earlier start of spring-time grazing by 6 and 3 weeks in 2019 and 2020, respectively. The difference between those years could be accounted for by differences in temperature and precipitation. The lengthening of the grazing season is of importance to dairy farmers in the peat meadow district as it is mostly limited by load bearing capacity and not grass production (Hoekstra et al., 2019). Assuming a grazing season of 27 weeks (end of March to start of October), extension of this season by 6 and 3 weeks would increase the grazing season by 22% and 11%, respectively. However, the grazing season cannot be extended indefinitely as a point will be reached when grass production and supply will be the limiting factors. In this study we do not take into account the potential extension of the grazing season in autumn. Even though sward density is likely to improve load bearing capacity in autumn, the coefficients of the prediction model will be different during the wetting process in autumn (as opposed to drying in spring).

Farmers are able to manipulate the sward density in different ways to extend their grazing season. The first pathway is through alteration of management. It is known that grazing creates a denser sward with a higher load bearing capacity compared to mowing (Altena & Hyink, 1971). Also, different grazing systems create different sward densities with altered load bearing capacity (Hoekstra et al., 2019). Strip grazing was found to have a more open sward while the 'Kurzrasen' method (continuous grazing at 4–6 cm sward height) was found to increase sward density (Hoekstra et al., 2019). Methods such as grazing with sheep during the winter period are known to increase sward density (Penning et al., 1991). Additionally, mowing with a higher frequency will increase the sward density (Korte, 1986).

The second pathway is the introduction of plant species that make a denser sward and have a more intensive rooting system. Grass species such as Kentucky bluegrass (*Poa pratensis*) (Dürr et al., 2005) and rough bluegrass (*Poa trivialis*) (Vartha, 1972) increase sward density through aboveground stolons. Historically they are considered as good quality forage grasses (Sikkema, 1989), even better than more commonly used species such as cock's foot (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*). Besides the different types of grass species, different degrees of sward density can be found in perennial ryegrass varieties. Diploid varieties tend to have a higher sward density and root biomass compared to tetraploids (Deru et al., 2014; Swift et al., 1993). In contrast, species such as white clover tend to have a lower rooting density (Caradus, 1990) and be more susceptible to damage through poaching (Bilotta et al., 2007; Menneer et al., 2005; Vertes et al., 1988).

5 | CONCLUSIONS

We can conclude that there is a positive correlation between load bearing capacity and sward density on peat soils. However, the effect of SMC seems to be larger in regard to load bearing capacity. The developed models showed an increase in load bearing capacity of 3 or 6 weeks, during spring 2019 and 2020 respectively, caused by an increase in sward density from 30% to 90%. Farmers can use this knowledge in their grassland management and species and cultivar selection. The newly developed method which measures impact depth was not more accurate than the generally used method of penetration resistance. However, it offer a valuable tool to quantify load bearing capacity in a way that allows for easy interpretation by farmers.

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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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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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