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Sward lifting in compacted grassland: Contrasting effects on two different soils

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ABSTRACT

Soil compaction can affect the productivity of permanent grassland. The effectiveness of methods to alleviate compaction depends on compaction level and soil type. We applied sward lifting in compacted grassland on a sandy loam and a heavy clay soil and measured effects on soil characteristics, grass roots, and grass productivity for a period of up to 32 months. Our results show that sward lifting improved soil structure in the heavily compacted sandy loam for at least 31 months. This led to an improvement in water drainage; sward-lifted plots dried up an estimated 10 days earlier than control plots in spring 2017. A likely earlier start of root growth resulted in a higher grass herbage yield (+12% to +22%) and nitrogen (N) uptake (+13% to +22%) in three first growth periods but in only relatively small gains over the entire experimental period (+4% and +8%, respectively). The higher herbage N uptake on sward-lifted plots over the experimental period (+76 kg N ha^{-1}) was offset by a small N loss (−67 kg N ha^{-1}) from the 0–30 cm soil layer. On the heavy clay, sward lifting also improved soil structure and rooting, but effects were smaller and shorter-lived, and herbage yield and N uptake tended to be lower over the entire experimental period (−6% and −5%, respectively). Here, the lower N uptake on sward-lifted plots over the experimental period (−43 kg N ha^{-1}) was accompanied by a large soil N loss (−613 kg N ha^{-1}). Based on all results, we conclude that sward lifting has limited attractiveness to alleviate compaction in water-retaining sandy soils when average penetration resistance in the topsoil is below 2.8 MPa. Sward lifting should be avoided on smectic clay soils altogether, as these soils have a high natural restoration capacity and sward lifting has more negative than positive effects.

1. Introduction

Soil compaction in permanent grassland is a problem, because it can impair grass growth through negative effects on root growth and root activity (Cook et al., 1996; Hopkins and Patrick, 1969). Its common occurrence and negative consequences have been recognized as a threat for European soils (Van-Camp et al., 2004; Van den Akker and Hoogland, 2011). A soil survey in the UK showed that 25–35% of grassland soils were in good soil structural condition, 54–63% in moderate condition, and 8–12% in poor condition (Newell-Price et al., 2013). Negative effects of compaction on productivity have economic consequences. For the Netherlands, we estimate a potential direct economic loss due to grassland compaction of €243–293 million annually for the 928,000 ha of grassland in agricultural use (CBS, 2018), when assuming an annual yield reduction of 1.38–1.66 Mg dry matter (DM) ha^{-1} (Bouwman and Arts, 2000; Douglas and Crawford, 1998) and applying an economic valuation of €0.19 per kg of DM (Blanken et al., 2017).

Sward lifting, a form of non-inversion tillage, is used as a method to alleviate compaction in the topsoil (0–30 cm) of permanent grassland, with minimal damage to sward and soil. Lifting and lowering of the topsoil creates a wave movement that breaks compacted layers into smaller parts while leaving the sward and roots largely intact. The latter is a significant advantage over the traditional method of grassland renovation by ploughing and reseeding. Apart from destructing the existing sward, the latter approach is costlier, may result in considerable losses of soil carbon, nutrients, and biodiversity (Necpálová et al., 2014; Van Eekeren et al., 2008), and may increase nitrate leaching and greenhouse gas emissions (Drewer et al., 2017; Shepherd et al., 2001). The minimal damage of sward lifting (De Boer et al., 2018) makes this method potentially useful to maintain permanent grassland, one of the focal points of the 2013 CAP reform of the EU and part of the EU regulations (EU Regulation Nº 1307/2013).

However, improvements in soil structure and rooting after sward lifting often do not increase herbage yield (Bhogal et al., 2011; Burgess

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et al., 2000; De Boer et al., 2018). If compaction is moderate or absent, sward lifting can even (temporarily) decrease yield (Bhogal et al., 2011; De Boer et al., 2018; Frost, 1988a,b). To assess potential benefits of sward lifting, this method should primarily be investigated in heavily rather than moderately compacted grasslands. Such studies are lacking.

The effects of alleviation by sward lifting can depend on soil compaction level and soil type. Wet soils with a high clay and a low organic matter (OM) content are more susceptible to compaction. On the other hand, swelling and shrinking of the clay fraction in heavy clay soils can reduce compaction naturally, through the production of (micro) cracks (Dexter, 1991). This process is in these soils also stimulated by a relatively high faunal activity (Drewry, 2006; Rutgers et al., 2009). In sandy soils, the physical and biological restoration capacity is smaller, and sward lifting may be the only possibility to alleviate compaction and restore grassland productivity without destroying the sward.

Measurement of herbage nitrogen (N) uptake is crucial to better understand the effects of soil cultivation methods, such as sward lifting, on soil N dynamics and grassland productivity. De Boer et al. (2018) found that an increase in herbage N uptake in the first growing season after sward lifting was reversed in the second growing season. Sward lifting may also have a larger effect on herbage N uptake than on herbage yield (De Boer et al., 2018). Burgess et al. (2000) stated that, at high N application rates, negative effects of compaction may show in N uptake while being masked in herbage yield. Unfortunately, herbage N uptake has often not been measured in relevant studies (Burgess et al., 2000; Carter and Kunelius, 1998; Drewry et al., 2000; Harrison et al., 1994).

Our objective was to further explore the potential of sward lifting as a method to alleviate soil compaction in heavily compacted grasslands. We tested this method in compacted permanent grassland on a sandy loam and a heavy clay soil, and measured effects on soil characteristics, grass roots, and grass productivity for over two growing seasons. We hypothesized that sward lifting would increase herbage yield and N uptake through an improvement of soil structure and rooting.

2. Materials and methods

2.1. Site properties

The experiment was conducted in compacted permanent grassland on two sites, located 8 km apart, in the Northern part of the Netherlands. Site 1, the sandy loam (53°13′48 N, 5°42′50E), was artificially drained, with drains every 10 m at 0.8 m depth. Despite the drainage, this site was prone to waterlogging throughout the year, due to severe compaction in both top- and subsoil. The soil profile was classified as a (homogenous) marine sandy loam and had been formed at higher elevation along a tidal stream, connected to a former inland sea (Middelzee). Soil properties of the 0–30 cm soil layer were: clay 11%, silt 35%, sand 52%, pH-KCl 6.4, OM 20 g kg^{-1}, total C 9 g kg^{-1}, total N 1.01 g kg^{-1}, P-Al 0.140 g kg^{-1}, K (0.01 M $CaCl_2$) 0.061 g kg^{-1}, and S (0.01 M $CaCl_2$) 0.010 g kg^{-1} (properties expressed on a DM basis). Because of the high silt content, this soil had a considerable groundwater capillary rise (up to 2 m; Bloemen, 1980) and was therefore largely drought-resistant throughout the growing season. A visual soil assessment, right before the start of the experiment, showed that the 0–6 cm soil layer had a good soil structure (high percentage of crumbs) and a high root density (see Section 2.4 for the assessment method). The 6–30 cm soil layer was highly compacted, had a low root density, no visibly active soil organisms, a very low number of macro pores, and showed signs of oxidation below 10 cm depth. Sandy loams are by nature sensitive to 'silting up', which results in compaction, poor natural drainage, and waterlogging. On this site, this sensitivity was exacerbated by a low soil OM content. This content had strongly declined during three years of arable cropping prior to the establishment of permanent grassland (2013). Furthermore, application of liquid dairy cattle manure by a trike (three-wheeled, self-propelling manure injector) in early spring in the years prior the experimental period, at a time when the soil is usually wet, had contributed considerably to the compaction. At the start of the experiment in 2015, the grass sward was three years old, and the species composition was dominated by perennial ryegrass (*Lolium perenne* L.) (abundance > 90%). In the years before the experiment, the grassland had been managed by cutting for silage, five times each growing season.

Site 2, the heavy clay (53°9′56 N, 5°45′37E), was also artificially drained, with drains every 10 m at 1 m depth. The soil profile was classified as a heavy marine clay and had been formed at the bottom of the aforementioned inland sea. Soil properties of the 0–30 cm soil layer were: clay 43%, silt 35%, sand 9%, pH-KCl 7.1, OM 109 g kg^{-1}, total C 56 g kg^{-1}, total N 6.03 g kg^{-1}, P-Al 0.122 g kg^{-1}, K (0.01 M $CaCl_2$) 0.081 g kg^{-1}, and S (0.01 M $CaCl_2$) 0.022 g kg^{-1} (properties expressed on a DM basis). In earlier analysis, the clay mineral fraction of this soil type had been characterized as smectic (65% of clay mineral montmorillonite, 5% vermiculite, 20% illite, 10% kaolinite), following the results of XRD-analysis (Moore and Reynolds, 1997). The groundwater capillary rise in this soil (up to 1.1 m; Bloemen, 1980) was considerably smaller than in the sandy loam, and this heavy clay was therefore more drought-sensitive. A visual assessment, right before the start of the experiment, showed that the 0–10 cm soil layer had a high percentage of crumbs, a high root density, and a high earthworm density (*Lumbricus terrestris*, *Aporrectodea caliginosa*). The 10–30 soil layer was increasingly compacted down to 30 cm depth, showing a low root density, absence of visibly active worms, and a low number of macro pores. Below 30 cm depth, old earthworm burrows were present, and compaction was less when compared to the layer above. At the start of the experiment, the grass sward was 20 years old, and its species composition was dominated by perennial ryegrass (72%) and rough meadow grass (*Poa trivialis* L.) (24%). In previous years, the grassland had been managed by cutting for summer feeding. This type of harvesting is carried out also when the soil is wet and was therefore likely the cause of the observed compaction.

2.2. Experimental design

Treatments were applied in the autumn (cf. De Boer et al., 2018) of 2015, and effects were measured in the growing seasons of 2016, 2017, and 2018 (up until the first growth period). At each site, the experiment was set up as a randomized complete block design, where treatments (control and sward lifting) were replicated in five blocks. Plot size was 10 × 2.7 m. Treatments were applied on 6 October 2015, after the last grass harvest of that growing season.

Sward lifting was carried out with a McConnel Grassland Shakaerator, equipped with four shanks spaced 60 cm apart and fitted with hardened, 24 cm-wide winged tines (McConnel, Ludlow, UK), at a depth of 30 cm. With this machine, the entire topsoil layer (0–30 cm, soil and sward) was lifted for 10–15 cm and lowered again. The machine was equipped with a vibration unit (via the power take-off), which caused the shanks and tines to vibrate when pulled through the soil. The aim of this vibration was to reduce draught, fuel consumption, and required horsepower (hp). The sward lifter was pulled through the soil by a 200 hp tractor.

The soil moisture content at the time of treatment application was estimated at 75–85% of field capacity (based on the soil reaction to treading and tractor trafficking) and cumulated rainfall within 10 days after treatment (27 mm) exceeded cumulated evapotranspiration (9 mm) (Royal Netherlands Meteorological Institute). Thus, conditions were optimal for sward lifting and sward recovery (cf. Burgess et al., 2000). After treatment, the only machine traffic on the plots was by a Haldrup harvester (wheel distance 0.9 m; weight 2030 kg) which passed over the centre of each plot lengthways during harvesting (five to six times in 2016, five times in 2017, and one time in 2018).

2.3. Grassland fertilization

The experiment included five harvest cycles (growth periods) per full growing season which were fertilized with synthetic fertilizer. The amount of annual N fertilization and its distribution over the growth periods was based on fertilizer recommendations and the estimated annual soil organic N mineralization (Anonymous, 2018). On the sandy loam, the plots received N fertilizer applications for the first five growth periods of 120, 90, 70, 50, and 40 kg N ha^{-1}, respectively. In 2017, the N application for the third growth period was increased from 70 to 85 kg N ha^{-1}, based on the growth response in the previous season. On the heavy clay, N fertilizer applications were 85, 60, 40, and 30 kg N ha^{-1} for the first four growth periods of 2016, respectively, and 95, 70, 50, 40, and 30 kg N ha^{-1} for the first five growth periods of 2017, respectively. In 2018, both sites received N fertilization for the first growth period only, amounting to 120 and 95 kg N ha^{-1}, respectively. The N fertilizer was applied either as ammonium sulphate (AS, 21% N, 24% S), sulphur-containing calcium ammonium nitrate (CAN-S, 24% N, 6% S), or standard CAN (27% N). In 2016, N fertilizer for the first growth period was applied as CAN-S. In 2017 and 2018, part of the N application for the first growth period was applied early in spring as a starter gift. This N was applied as AS and amounted to 15 kg N ha^{-1} in 2017 and 40 kg N ha^{-1} in 2018. The remainder of the N application for the first growth period of 2017 and 2018 was applied at a regular date as CAN-S. After the first growth period, all N fertilizer was applied as standard CAN. In addition to N application, plots received applications of 9 kg P ha^{-1} and 33 kg K ha^{-1} for each of the growth periods. The P fertilizer was applied as triple super phosphate (20% P) and the K fertilizer as KCl (50% K). All fertilizers were evenly distributed over each individual plot by hand, by a trained employee of the research facility (Dairy Campus). Fertilizer for the first growth period was in 2016 applied on April 11 (CAN-S), in 2017 on March 6 (AS) and April 10 (CAN-S), and in 2017 on March 5 (AS) and April 9 (CAN-S). After the first growth period, fertilizer for the following growth periods was applied immediately after harvest of the preceding growth period.

2.4. Soil measurements

Soil measurements were of soil bulk density, soil penetration resistance, soil fertility (OM, C, and N content), root biomass, water drainage rate (spring), and also included a visual assessment of soil structure, root density, and earthworm activity.

Soil bulk density was measured 30 months after treatment application (March 2018), to 30 cm depth and in three 5-cm layers per plot: 5–10 cm, 15–20 cm, and 25–30 cm. Two undisturbed ring samples containing 100 cm^3 soil were taken from each soil layer per plot, at two positions, at least 50 cm inside the plot borders. The rings were weighed, oven-dried for 24 h at 105 °C, re-weighed, and the results were averaged per soil layer per plot.

Soil penetration resistance was measured 7, 13, 18, 25, and 30 months after treatment application (May and November 2016, March and November 2017, March 2018) with a penetrologger (cone area 1 cm^2, apex angle 60°; Eijkelkamp, The Netherlands), at 1-cm depth intervals to 80 cm depth, in 10 randomly chosen positions in each plot, at least 50 cm inside of the plot borders (cf. Campbell and O'Sullivan, 1991). The soil water content was near field capacity during measurements in November and March, providing optimal conditions for penetration resistance measurements (cf. Smith et al., 1997). On the observation date in May 2016, the soil was too dry for reliable measurement, and on the observation date in November 2017, a methodological error was made while measuring the clay soil. Therefore, the results of these measurements are not reported or discussed.

Soil OM, C, and N content were measured 30 months after treatment application (March 2018). The soil was sampled to 30 cm depth, in three 10-cm layers, at 10 positions in each plot (equally distributed over the plot area), and at least 50 cm inside of the plot borders. Soil samples were pooled per soil layer per plot and oven-dried for 48 h at 70 °C. Organic matter was determined by loss-on-ignition (NEN 5754, 2005) and total C and N by elementary analysis following dry combustion (LECO CN analyzer). The amounts of soil OM, C, and N per hectare were calculated per treatment for each 10-cm layer and for the 0–30 cm layer, using the soil analysis results per treatment, and the soil bulk densities per layer of the control treatment (to base comparisons between treatments on the same amount of soil, as sward lifting may affect bulk density and thus the amount of soil per layer). Bulk densities in the 5-cm layers were used as representative for the 10-cm layers. This may have resulted in a slight overestimation of the calculated amounts, as bulk density usually increases with depth, but any impact on differences between treatments should have been minimal.

Root biomass was sampled 7, 13, 19, and 25 months after treatment application (May and November 2016 and 2017), on the sandy loam only. In each plot, three soil cores (82 mm diameter) were taken from four soil layers (0–10, 10–20, 20–30, and 30–40 cm), using a root auger (Eijkelkamp, The Netherlands). The cores were pooled per soil layer per plot and washed over a 2-mm mesh screen. Organic debris were picked and removed, and samples were oven-dried for 24 h at 70 °C to determine root dry weight and to calculate root biomass per hectare.

Water drainage rate was measured in the early spring of 2017, on the sandy loam only. For these measurements, the soil core holes left from root biomass sampling on the previous observation date (November 2016) were used. These holes filled with water during rainfall and drained slowly after rainfall had stopped. We used the rate of water level decline in the core holes as a proxy for water drainage rate. Measurements started on February 26, when all cores holes were water-filled to soil surface level, and measurements were repeated after 6, 9, 12, 14, 16, and 18 days. On each observation date, core hole depth (cm) and water level in the hole below soil surface (cm) were measured for each individual core hole and averaged per plot. The observational period was ended after 16 days for the sward-lifted plots, because some holes were almost dry, and after 18 days for the control plots.

Visual assessment of soil structure, root density, and earthworm activity took place in the 0–25 cm soil layer, 7, 13, 19, and 25 months after treatment application (May and November 2016 and 2017). Cubes (one per plot, each time at a different position) were dug out with a spade and broken in both horizontal and vertical direction. Soil structure was assessed by estimating the proportion (%) of soil crumbs, subangular blocky elements, and angular blocky elements in the cubes, following the method by Peerlkamp (1959) and Shepherd (2000). Rooting was assessed by scoring visible root density (score 1–10; 1 for no roots and 10 for above average) and estimating the proportion of young roots relative to total roots. Earthworm activity was assessed by scoring the quantity of visible earthworm burrows (relative score 1–10; 1 for no burrows and 10 for above average).

2.5. Sward measurements

Sward measurements were of herbage yield, herbage N uptake, and botanical composition. Herbage yield was determined by cutting the grass with a Haldrup grass harvester (J. Haldrup a/s, Løgstør, Denmark) to a height of 6 cm, from the 15-m^2 centre of each plot. The harvested material was weighed, and samples were oven-dried for 48 h at 70 °C to determine dry weight and calculate herbage biomass and N uptake per hectare. Total N content in the dried samples was determined by a Dumas-based method (NEN 16634-1, 2008). In 2016, the plots were harvested on May 9, June 10/14, July 22, August 25, September 29, and November 1 (clearing cut, sandy loam only); in 2017 on May 9, June 12, July 17, August 22, and September 26; and in 2018 on May 8.

The assessment of botanical composition took place 8, 11, 20, and 25 months after treatment application (May and September 2016, May and October 2017). The assessment followed the method by Sikkema (1997) and consisted of visually estimating the relative soil cover by the sward and the proportion of each species therein (relative abundance).

2.6. Statistical analysis

Data were tested for normality and homogeneity. Thereafter, treatment effects were analyzed for each location separately, using the ANOVA-procedure in the Genstat statistical package (18th edition; VSN International, Hempel Hempstead, UK). Soil bulk density and penetration resistance were analyzed per 10-cm soil layer, for penetration resistance based on the average of ten (1-cm increment) observations per layer. The amounts of soil OM, C, N, and root biomass were analyzed per 10-cm soil layer and as a total of all layers. Water level in the soil core holes, visual soil structure, root density, earthworm activity, and sward botanical composition were analyzed per observation date. Herbage yield and N uptake were analyzed per individual harvest as well as for cumulative harvests per growing season.

3. Results

3.1. Belowground

3.1.1. Soil bulk density and soil fertility

On the sandy loam, sward lifting did not significantly ($P > 0.05$) influence soil bulk density in the 5–10 cm soil layer, but resulted in significantly ($P \leq 0.05$) lower bulk densities in the 15–20 cm and 25–30 cm soil layers, measured 30 months after treatment (Table 1). On the heavy clay, soil bulk density was not significantly influenced in any of the soil layers, measured 30 months after treatment.

Soil fertility parameters (amounts of OS, C, and N), measured 30 months after treatment, appeared lower on both soil types after sward lifting, except for the amount of C in the sandy loam. Differences were, however, only occasionally significant (Table 1). On the sandy loam, there were no significant differences between treatments in the amounts of OM, C, and N, neither in the 0–30 cm soil layer nor in individual 10-cm soil layers. On the heavy clay, the amount of OM was significantly lower in the 0–30 cm soil layer of the sward-lifted plots when compared to the controls, and the amount of C tended to be lower. The amount of N was not significantly different between the treatments in the 0–30 cm soil layer, but was significantly lower ($P = 0.01$) in the 10–20 cm layer for the sward-lifted plots compared to the controls, and was 6044 and 6480 kg N ha^{-1}, respectively.

3.1.2. Soil penetration resistance

Sward lifting reduced soil penetration resistance for at least 30 months (last observation) on both soil types (Fig. 1). On the sandy loam, penetration resistance in the 10–30 cm soil layer was significantly lower ($P < 0.01$) on all observation dates. Resistance in the 0–10 cm layer was lower after 13 and 18 months ($P < 0.01$) and tended to be lower after 30 months ($P = 0.06$). Noteworthy, penetration resistance was 25 months after treatment also significantly lower ($P = 0.02$) in the 70–80 cm layer, for the first time. After 30 months, it was not only lower in the 70–80 cm layer ($P = 0.04$) but also in the 60–70 cm layer ($P = 0.05$), for the first time, and it tended to be lower ($P = 0.08$) in the 30–40 cm layer, for the first time. Thus, one event of sward lifting influenced more and deeper soil layers over the course of the observational period. On the heavy clay, penetration resistance was significantly lower in the 10–40 cm layer ($P < 0.05$), on all observation dates.

3.1.3. Water drainage rate

Water level in the soil core holes (below field level) was significantly lower ($P < 0.01$) in the sward-lifted plots compared to the control plots, on all observation dates except t = 0 days (Fig. 2). The slope of the decline in water level over time, which indicates water drainage rate, was comparable for both treatments from six days after start of observations onwards. At that time, water level in the holes was 2.4 and 13.7 cm below field level for the control and sward-lifted plots, respectively. Holes in the sward-lifted plots dried up 17 days after start of observations, an estimated 10 days earlier than holes in the control plots (based on the difference in drainage rate).

3.1.4. Root biomass

Sward lifting influenced root biomass in the sandy loam in the 10-cm soil layers and in the total 0–40 cm layer, as measured after 7, 13, 19, and 25 months (Fig. 3). After 7 months (May 2016), root biomass was significantly higher in the 0–10 cm and 20–30 cm soil layers of sward-lifted plots compared to the controls ($P = 0.05$ and $P = 0.01$, respectively). Total root biomass was also higher ($P = 0.03$). After 13 months (November 2016), root biomass in the 0–10 cm soil layer tended to be lower ($P = 0.08$) and total root biomass was lower ($P = 0.04$). After 19 months (May 2017), root biomass in the sward-lifted plots was significantly lower in the 10–20 cm soil layer ($P = 0.04$) and total root biomass tended to be lower ($P = 0.08$). After 25 months (November 2017), there were no longer significant differences nor tendencies to significant differences in root biomass between sward-lifted and control plots. Noteworthy, root biomass in the second growing season was about double the amount measured in the first growing season.

3.1.5. Soil structure, root density, and earthworm activity

On the sandy loam, sward lifting had a positive effect on soil structure, root density, proportion of young roots, and earthworm activity in the 0–25 cm soil layer, for at least 25 months (final observation) (Table S1, supplementary material). However, effects were variable between observation dates. On the heavy clay, sward lifting had a positive effect on soil structure and earthworm activity in the 0–25 cm soil layer for 19 months, but here effects were smaller and more variable than on the sandy loam (Table S1). Whereas total root density was higher for 13 months, the proportion of young roots was not influenced by sward lifting.

Table 1
Bulk density (g cm^{-3}) and amounts of organic matter (Mg ha^{-1}), carbon (Mg ha^{-1}), and nitrogen (kg ha^{-1}) in soil layers of compacted grassland on a sandy loam and heavy clay soil, 30 months after sward lifting in the autumn of 2015 and compared to the untreated controls.

		Sandy loam			Heavy clay		
Characteristic	Soil layer (cm)	Treatment Control	Lifting	P-value[1]	Treatment Control	Lifting	P-value
Bulk density	5-10	1.45	1.40	0.16	0.74	0.74	0.83
	15-20	1.58	**1.53**[2]	0.01	1.06	1.12	0.17
	25-30	1.57	**1.49**	0.02	1.14	1.10	0.45
Organic matter	0-30	122.7	118.6	0.37	362.8	**348.4**	0.01
Total carbon	0-30	48.2	48.2	1.00	157.2	149.2	0.10
Total nitrogen	0-30	5114	5047	0.64	16122	15509	0.34

[1] $P \leq 0.05$ indicates a significant difference.
[2] A bold font indicates a significantly different value for the lifting treatment compared to the control.

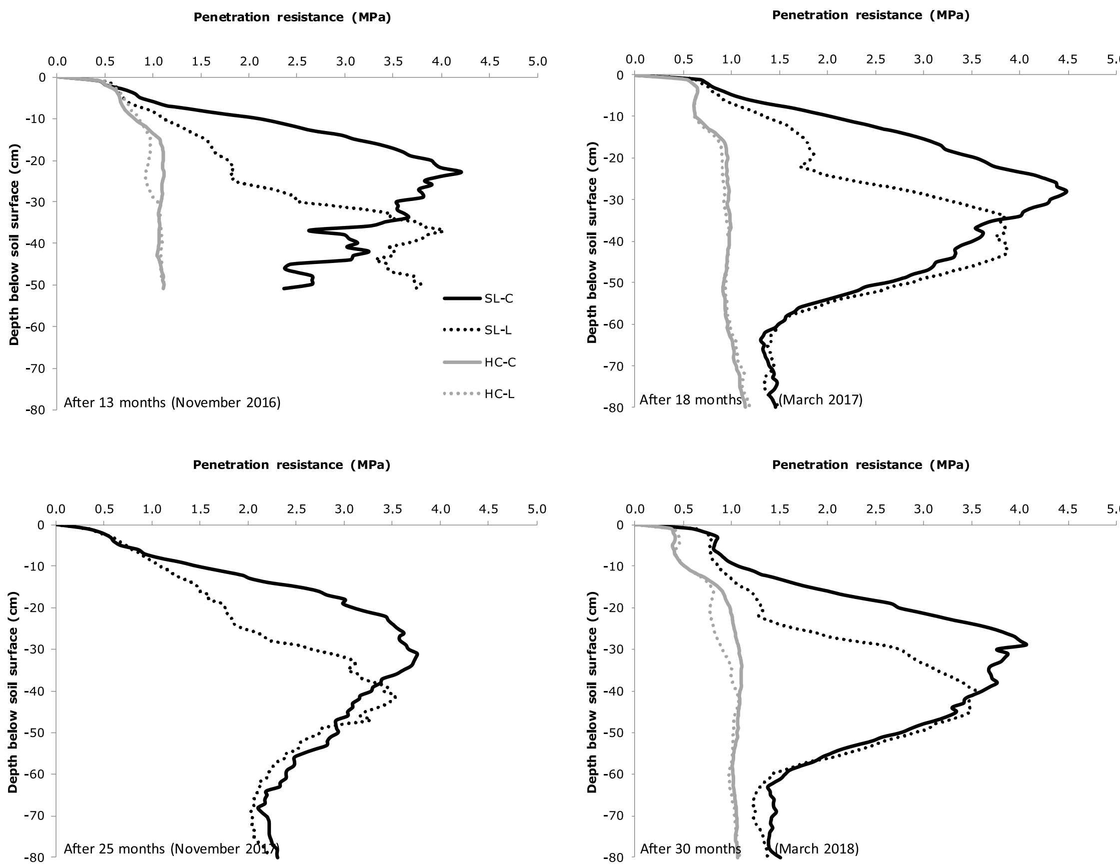

Fig. 1. Penetration resistance (MPa) in the 0–80 cm soil profile of compacted grassland on a sandy loam (SL) and heavy clay (HC), as influenced by sward lifting (L) and compared to the untreated control (C). Measurements were 13, 18, 25, and 30 months after treatment in the autumn of 2015. Results for heavy clay after 25 months are not reported, because a methodological error was made during measurement.

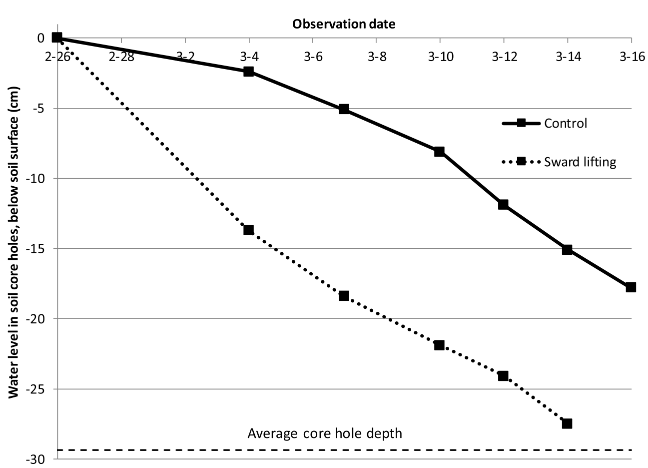

Fig. 2. Decline in the water level of initially water-filled soil core holes in grassland on a heavily compacted sandy loam, as influenced by sward lifting and compared to the control treatment, measured in early spring 2017. The decline in water level over time is used as a proxy for water drainage rate.

3.2. Aboveground

3.2.1. Herbage dry matter yield

On the sandy loam, sward lifting had a positive effect on herbage yield of the first growth period of all three growing seasons, when compared to the controls, and this difference was significant in the first two growing seasons (Table 2). Yield of later growth periods was not significantly influenced in either of the two full growing seasons. The cumulative yield of the first growing season tended to be higher due to sward lifting, whereas the cumulative yield of the second growing season was not significantly influenced.

On the heavy clay, sward lifting had a significant positive effect on the yield of the first growth period of the first growing season, but yield of the following growth period tended to be lower, and yields of the fourth and fifth growth periods were significantly lower (Table 2). The cumulative yield of the first growing season was not significantly influenced by sward lifting. In the second growing season, yield of the first and third growth period tended to be lower on the sward-lifted plots compared to the controls, and yield of the second growth period was significantly lower. Cumulative yield of the second growing season was also significantly lower. In the third growing season, yield of the first growth period was significantly lower on the sward-lifted plots compared to the control plots.

3.2.2. Herbage nitrogen uptake

On the sandy loam, sward lifting increased N uptake in the first growth period of all three growing seasons when compared to the controls, and the difference was significant in the first two growing seasons (Table 3). In the first growing season, sward lifting also significantly increased N uptake in the third and fifth growth period, and cumulative N uptake of the entire season. In the second growing season, N uptake after the first growth period was not significantly influenced by sward lifting, and neither was the cumulative N uptake of that season.

On the heavy clay, sward lifting significantly increased N uptake in the first growth period of the first growing season after treatment, but decreased N uptake in the fifth growth period of that season (Table 3). The N uptake in other growth periods was not influenced by sward lifting, except for the first growth period of the third growing season,

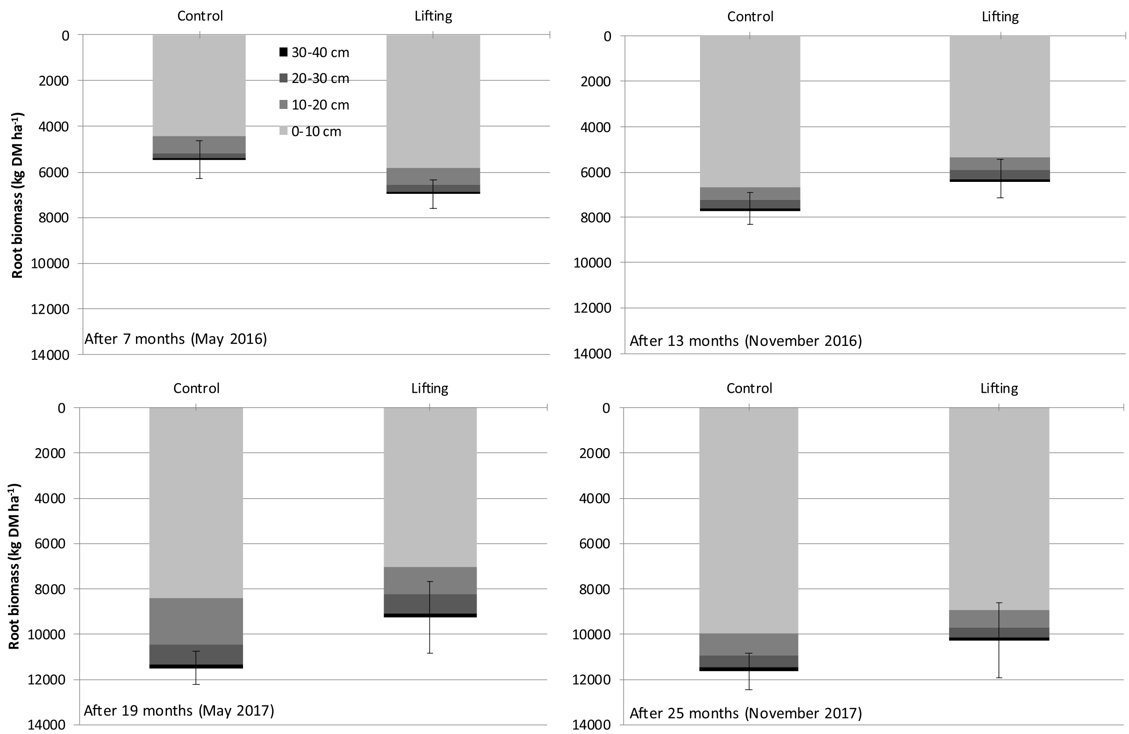

Fig. 3. Root biomass in the 0–10, 10–20, 20–30, and 30–40 cm soil layers of a compacted grassland on a sandy loam, as influenced by sward lifting (SL) and compared to the untreated control (C). Measurements were 7, 13, 19, and 25 months after sward lifting in the autumn of 2015. Error bars represent 2 x standard errors of total root biomass (0–40 cm soil layer).

Table 2
Herbage yield (kg DM ha^{-1}) of compacted grassland on a sandy loam and heavy clay soil, as influenced by sward lifting in the autumn of 2015 and compared to the untreated control.

Year	Harvest #	Sandy loam			Heavy clay		
		Treatment Control	Lifting	P-value[1]	Treatment Control	Lifting	P-value
2016	1	3665	**4205**[2]	< 0.001	4013	**4266**	0.05
	2	4730	4762	0.85	4227	3932	0.07
	3	4020	4276	0.46	3323	3451	0.33
	4	2306	2308	0.98	1940	**1771**	0.01
	5	2250	2330	0.22	1125	**974**	0.01
	6	426[3]	439	0.07	-[4]	–	–
	Total	17397	18320	0.10	14628	14394	0.32
2017	1	3810	**4181**	0.01	4070	3792	0.09
	2	4560	4446	0.11	3515	**3079**	0.03
	3	3488	3388	0.47	2815	2583	0.09
	4	3626	3599	0.79	2673	2537	0.41
	5	2064	2048	0.66	1746	1538	0.25
	Total	17548	17662	0.72	14819	**13529**	0.02
2018	1	2981	3435	0.25	4298	**3895**	0.03

[1] $P \leq 0.05$ indicates a significant difference.
[2] A bold font indicates a significantly different value for the lifting treatment compared to the control.
[3] Clearing cut before winter.
[4] Clearing cut not necessary.

Table 3
Nitrogen uptake (kg N ha^{-1}) of compacted grassland on a sandy loam and heavy clay soil, as influenced by sward lifting in the autumn of 2015 and compared to the untreated control.

Year	Harvest #	Sandy loam			Heavy clay		
		Treatment Control	Lifting	P-value[1]	Treatment Control	Lifting	P-value
2016	1	99	**120**[2]	0.00	117	**131**	0.05
	2	120	126	0.51	96	95	0.81
	3	89	**96**	0.04	83	77	0.32
	4	59	60	0.69	53	51	0.14
	5	58	**61**	0.02	32	**28**	0.02
	6	14[3]	14	0.16	-[4]	–	–
	Total	438	**478**	0.04	381	382	0.96
2017	1	99	**112**	0.01	119	114	0.23
	2	133	140	0.26	89	79	0.11
	3	100	100	0.90	72	71	0.22
	4	89	90	0.79	85	82	0.38
	5	46	49	0.14	54	52	0.52
	Total	466	490	0.21	419	397	0.10
2018	1	93	105	0.26	143	**121**	0.04

[1] $P \leq 0.05$ indicates a significant difference.
[2] A bold font indicates a significantly different value for the lifting treatment compared to the control.
[3] Clearing cut before winter.
[4] Clearing cut not necessary.

when N uptake of sward-lifted plots was lower compared to the controls. Cumulative N uptake in either of the two full growing seasons was not influenced by sward lifting.

3.2.3. Sward botanical composition

On the sandy loam, sward lifting did not significantly influence sward cover as measured after 8 months, but resulted in a (slightly) lower cover after 11, 20, and 25 months (Table S2). The relative abundances of species present, *L. perenne* L. (95%), *Poa trivialis* L. (3%), *Phleum pratense* L. (2%), and *Poa annua* L. (1%), were not significantly influenced (as measured after 25 months).

On the heavy clay, sward cover was not significantly influenced as measured after 8 months, but was (slightly) decreased after 11, 20, and 25 months (Table S2). Sward lifting did not influence the relative abundance of *L. perenne* as measured after 8 months, but tended to decrease its abundance after 11 months and decreased it significantly after 20 and 25 months. The relative abundance of *Poa trivialis* tended to be higher when measured after 8 months, was not influenced after 11 months, tended to be higher after 20 months, and was significantly higher after 25 months. The relative abundances of other species present, *Poa annua* L. (1%) and *Elymus repens* L. (1%), were not influenced by sward lifting (as measured after 25 months).

4. Discussion

4.1. Sandy loam

Sward lifting resulted on the heavily compacted sandy loam in a lasting improvement of the soil structure, as indicated by differences in bulk density, penetration resistance, and visual assessments. These improvements resulted in a higher water drainage rate; sward-lifted plots dried up an estimated 10 days ahead of the control plots in spring 2017. Earlier drying of the soil promotes an earlier increase in air-filled pore volume (Sveistrup and Haraldsen, 1997), followed by an increase in root growth, grass growth, and grass N uptake. The improvements in soil structure resulted in a general improvement of grass rooting throughout the growing season, visible by a higher root density and proportion of young roots (Table S1). Total dry root biomass, however, was only higher when measured 11 months after sward lifting; at later observation dates, total root biomass was lower for the sward-lifted plots compared to the controls. The contrast between the results of visual root assessments and root biomass measurements may be explained by the fact that root biomass measurements include both living and dead roots. Because soil loosening by sward lifting increases the air-filled pore volume, the activity of soil microorganisms and fauna is also increased (Brevik et al., 2002; De Neve and Hofman, 2000; Douglas et al., 1998). The latter was in the present study confirmed by the higher score for earthworm activity (as measured after 13 months or later) (Table S1). An increased soil microbial and faunal activity may result in an accelerated decomposition of OM in dead roots and consequently in a lower total dry root biomass at later observation dates. An accelerated OM decomposition was in the present study confirmed by the lower amount of OM in the soil of sward-lifted plots compared to the controls (Table 1). An effect of an accelerated decomposition of dead roots on total root biomass was likely exacerbated by the relatively low OM content of young roots. The latter results in a relatively small contribution to total dry biomass of young roots when compared to older roots. Thus, it is possible that sward lifting results in a decrease in total root biomass despite an increase in the biomass of young, active roots.

The improvements in soil structure, water drainage rate, rooting, and earthworm activity after sward lifting did not result in a consistently higher grass herbage yield and N uptake. Herbage yield and N uptake were only both higher in the first growth period of all three growing seasons. The difference in N uptake in the first growth period after sward lifting was relatively large when compared to the difference in the first growth period of the second and third growing season. This extra effect was likely the result of a temporarily increased soil N mineralization after sward lifting (De Boer et al., 2018). The higher N uptake in the later first growth periods could potentially be explained by an earlier start of the soil organic N mineralization in spring, due to the earlier increase in air-filled pore volume in the sward-lifted plots. However, N mineralization rate is relatively low in early spring, and the organic N content of the sandy loam was also low; the annual N supply by mineralization was for this soil estimated at 70 kg N ha^{-1} $year^{-1}$, based on the N content of the 0–10 cm layer (Anonymous, 2018). Verloop et al. (2014) measured in permanent grasslands on sandy soil an average daily N mineralization in March of 0.2% of the annual N mineralization. Applying this relative N mineralization rate to the sandy loam translates into a total amount of 1.4 kg ha^{-1} mineralized N over a 10-day period. It appears therefore unlikely that a 10-day earlier start of N mineralization in the first half of March 2017 resulted in a difference in N uptake due to sward lifting of 13 kg N ha^{-1} in the first growth period of that year (Table 3). Another possible, partial explanation for this higher N uptake on the sward-lifted plots is a lower (gaseous) N loss by denitrification from the drier and less compacted sward-lifted plots in early spring (Bhandral et al., 2007; Yamulki and Jarvis, 2002). However, this effect is not likely to have contributed to the differences in N uptake in the first growth period of the second and third growing season, when a starter gift was applied as ammonium-N, and nitrate-containing CAN was applied only when the plots had largely dried up (9–11 April). Furthermore, N uptake was not affected when plots were waterlogged for a period of up to two weeks in the fourth growth period of 2017 (Table 3). This makes an explanation from differences in N loss by denitrification less plausible. The major part of the higher N uptake on the sward-lifted plots in the first growth period may best be explained by a higher uptake of fertilizer N following the improved rooting characteristics (Kristensen and Thorup-Kristensen, 2004; Popay and Crush, 2009). Although total root biomass (including dead roots) was lower after sward lifting, root density and the proportion of young roots were higher in spring 2016 and 2017 (2018 not measured), as observed right after harvest of the first growth period (Table S1).

The higher herbage N uptake on the sward-lifted plots over the entire experimental period (76 kg N ha^{-1}) was largely offset by a concurrent loss of 67 kg N ha^{-1} from the soil N stock (Table 1). It may be argued that the difference in N stock between control and sward-lifted plots was not significant, and thus non-existent, but there is ample evidence for soil loosening to increase soil N mineralization (e.g. Kristensen et al., 2003) and thus potential N loss. In November 2015, grass on the sward-lifted plots was darker green of colour than on the control plots, a visual indication that extra N had been taken up on the sward-lifted plots. This extra uptake was likely only part of the extra-mineralized N, with the remainder being lost over the following winter by nitrate leaching and denitrification (Drewer et al., 2017; Shepherd et al., 2001). We conclude that the loss of N from the soil stock offset the higher N uptake by the crop and that the additional losses in soil OM and C are undesirable from a wider agronomical perspective. Moreover, the relatively small gain in herbage yield over two full growing seasons (+3%) limited the benefits of a sward lifting treatment on this heavily compacted soil.

4.2. Heavy clay

On the heavy clay, which was less compacted than the sandy loam, sward lifting also improved soil structure as measured by penetration resistance and visual soil assessment, but here effects were smaller, more variable, and lasted for a shorter period. The improvements in soil structure also resulted in a higher root density but not in a higher proportion of young roots (Table S1). Moreover, the effect on root density disappeared 1–1.5 years after sward lifting. The improvements in soil structure, root density, and earthworm activity did not result in a structural improvement of herbage yield and N uptake. Herbage yield and N uptake were only higher in the first growth period after sward lifting and were regularly lower afterwards. A higher herbage yield and N uptake in the first growth period after soil loosening is often observed, as the result of a temporarily increased soil organic N mineralization (De Boer et al., 2018). The tendency to a lower herbage yield and N uptake afterwards may have been caused by the relatively large decrease in soil N fertility due to sward lifting. At the end of the observational period, the N stock in the 0–30 cm soil layer was 613 kg ha^{-1} lower in the sward-lifted plots when compared to the controls (Table 1). Likely, most of this N was lost during the winter period after sward lifting, comparable to the situation on the sandy loam. Whereas the soil N loss from the sandy loam was compensated for by a higher herbage N uptake, the soil N loss from the heavy clay was complemented by a slightly lower herbage N uptake of 43 kg N ha^{-1} over the experimental period. As a result, recorded total N loss from the system (soil + sward) was 656 kg N ha^{-1} at the end of the experiment.

The observed tendency to a lower herbage yield and N uptake may also be explained by negative effects of a deteriorated soil (macro) structure. In August 2016, after a dry period, more and larger soil cracks were visible in the sward-lifted plots compared to the controls. This structural damage may have had consequences for the water supply, e.g. by earlier drying out of the soil or interruption of capillary rise pathways, making the grass on the sward-lifted plots more sensitive to water shortage when compared to the controls. Some evidence for a negative effect of sward lifting on water supply is found in the relatively large decline in herbage yield when compared to the decline in N uptake, e.g. in the dry fourth growth period of 2016 (Tables 2 and 3).

The soil compaction that was present in the heavy clay soil in the autumn of 2015, before the start of the experiment (see Section 2.1), had largely disappeared in the control plots in the spring of 2016. Our interpretation is that this heavy clay soil can reverse compaction naturally, through the swelling and shrinking of the smectic clay fraction and a high soil faunal activity. Under these conditions, sward lifting had the opposite effect on soil structure and grass growth than was hypothesized. Heavy smectic clay soils with a high soil faunal activity should therefore not be tilled to alleviate compaction, but rather be left to the process of natural restoration.

4.3. Sward lifting threshold

Measurement of the effects of sward lifting on soil penetration resistance and herbage yield, when compared to the control treatment, makes it possible to relate this information and to formulate a potential sward lifting treshold, i.e. the level of soil compaction at which sward lifting improves grassland productivity. In a previous study, we concluded that sward lifting did not improve grassland productivity on a moderately compacted sandy soil, despite improved soil structure and rooting characteristics (De Boer et al., 2018). Apparently, the compaction level in that soil (on average 2.1 MPa penetration resistance in the 5–25 cm wet soil profile) was below the threshold at which grassland productivity is negatively influenced. These earlier results confirmed findings by Carter and Kunelius (1998), who reported negative effects of sward lifting on herbage yield at a penetration resistance of on average 1.9 MPa in the 5–25 cm wet soil profile of a sandy loam. The sandy loam in our study was chosen because of its extreme compaction, having a penetration resistance of on average 2.8 MPa in the 5–25 cm wet soil profile and of 3.9 MPa in the 20–30 cm wet soil layer (at the first reported measurement, 13 months after sward lifting; Fig. 1). Sward lifting reduced these penetration resistances to on average 1.4 and 2.0 MPa, respectively. Because sward lifting had positive effects on herbage yield and N uptake of the first growth periods, it appears that on this sandy loam the sward lifting threshold had been crossed. However, the increase in N uptake was largely offset by the N loss from the soil N stock. We therefore conclude that sward lifting of grassland on sandy (loam) soils has limited attractiveness when the penetration resistance in the 5–25 cm wet soil layer is below a level of on average 2.8 MPa. However, two important points must be made, namely: i) the (severe) compaction in the subsoil (30–60 cm) was not alleviated, neither by sward lifting or natural processes (Fig. 1), and ii) the investigated sandy loam had a good water supply throughout the growing season. Alleviation of the (severe) compaction in the subsoil would likely have further improved the draining of excess water in early spring and likely have resulted in an earlier start of root growth, more root growth at depth (Sveistrup and Haraldsen, 1997), the interception of more fertilizer N by these roots (Popay and Crush, 2009), a higher herbage N uptake, and a higher herbage yield. Furthermore, positive effects of the alleviation of subsoil compaction (Van den Akker et al., 2003) are likely to be exacerbated on drought-sensitive sandy soils, where deeper rooting is critical for a higher interception of N and for water uptake in dry periods. Given the previous points, a tentative sward lifting threshold of 2.8 MPa penetration resistance only holds when it applies to the topsoil of water-retaining sandy (loam) soils. For heavy smectic clay soils, sward lifting is not advisable.

5. Conclusion

Sward lifting in grassland on a heavily compacted sandy loam increased its productivity, but only in spring. Given the concurrent loss in soil fertility, this treatment was not attractive when judged from a wider agronomical perspective. The relatively small productivity response to the successful alleviation of heavy compaction brings forward the general question whether compaction of the topsoil (0-30 cm) is problematic enough to warrant this type of treatment. Likely, treatment of the topsoil should be complemented with treatment of the subsoil (e.g. 30–60 cm). Deeper treatment, particularly on compacted drought-sensitive sandy soils, could give a more satisfactory productivity response and should therefore be investigated. The results of such additional work will help to further delineate a sward lifting threshold value for sandy soils, which for now we tentatively set at a soil penetration resistance of 2.8 MPa. Finally, our results demonstrate that sward lifting in existing grassland on heavy smectic clay soils should be avoided, not only given the observed negative effects, but especially when considering the natural restoration capacity of these soils.

Declaration of Competing Interest

The authors declare they have no conflict of interests.

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Appendix A. Supplementary data

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