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Sward lifting in compacted grassland: effects on soil structure, grass rooting and productivity

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ABSTRACT

Soil compaction can impair the productivity of permanent grassland. A way to ameliorate compaction in the topsoil (0–30 cm), without destroying the sward, is soil loosening by sward lifting. To explore the potential of this form of non-inversion tillage, we applied this treatment once, either in spring or in autumn, to a moderately compacted grassland on a sandy soil and measured the effects on soil structure, grass rooting and productivity for up to two growing seasons. We also explored whether complementary overseeding with *Lolium multiflorum* Lam. would extend the duration of soil loosening effects. Our results show that sward lifting improved soil structure and rooting for at least 10–12 months, but did not result in a consistent or lasting increase in herbage yield or nitrogen (N) uptake. Loosening in spring decreased herbage yield (−27%) and N uptake (−16%) in the following growth period, but these decreases were largely compensated for (herbage yield) or more than compensated for (N uptake) by increases in the next three growth periods. The increase in N uptake in the first growing season (+13 kg N ha^{-1}) was reversed in the second season (−14 kg N ha^{-1}). Loosening in autumn increased herbage yield (+8%) and N uptake (+15%) in the first growth period (after winter), but not in the four growth periods thereafter. Cumulative yield tended to be higher (+4%), which supports the view that soil loosening should be carried out in autumn rather than in spring. The initial positive effects of loosening on herbage yield and N uptake were explained by a temporary increased soil N mineralization; initial negative effects by mechanical damage to sward and roots. Finally, complementary overseeding did not extend the duration of soil loosening effects; apparently, new root growth from the existing sward was effective enough to stabilize these effects.

1. Introduction

Soil compaction is a common problem in permanent grassland. It is caused by machine traffic (Douglas and Crawford, 1991; Frost, 1988a), livestock treading (Greenwood et al., 1997; Mulholland and Fullen, 1991) and natural soil consolidation (Carter, 1990). Soil compaction may affect root growth and activity, e.g. through physical impedance and oxygen deprivation (Cook et al., 1996; Hopkins and Patrick, 1969), and hence impair crop growth. Compaction probably affects a considerable area of grassland worldwide. In a soil compaction survey in the UK, only 30% of grassland soils were found to be in good soil structural condition; 60% in moderate condition and 10% in poor condition (Newell Price et al., 2012).

Soil compaction can be ameliorated, although prevention is more effective (Douglas, 1994). To a certain extent, compaction is reversed by natural soil processes that produce (micro) cracks (Dexter, 1991), such as soil wetting followed by drying, and soil freezing followed by thawing. This natural restoration process is further enhanced by the formation of macropores through earthworm activity and through root penetration followed by root decay (Dexter, 1991; Drewry, 2006). When, in grasslands, these processes are not sufficient to ameliorate compaction, various mechanical soil loosening methods can be applied, including slitting, spiking, sward lifting and subsoiling (Bhogal et al., 2011). Sward lifting, a form of non-inversion tillage, can be applied to ameliorate compaction in the topsoil layer (0–30 cm). Lifting and lowering of the topsoil creates a wave movement that breaks the compacted layers into smaller pieces, while leaving the sward and roots largely intact. The latter is a significant advantage over a more traditional method to ameliorate compaction, grassland renovation by ploughing and reseeding. Apart from the destruction of the existing sward, this approach is also more costly, may result in considerable losses of soil carbon, nutrients and biodiversity (Necpálová et al., 2014;

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Van Eekeren et al., 2008), and may increase nitrate leaching and greenhouse gas emissions (Drewer et al., 2017; Shepherd et al., 2001).

Sward lifting has been found to improve grassland topsoil structure, with effects persisting for up to several years (Carter and Kunelius, 1998; Drewry et al., 2000). However, soil structure improvements do not necessarily translate into higher herbage yields. In various experiments, mechanical soil loosening was found to have no effect on grass yield, which can be ascribed to experimental shortcomings (Burgess et al., 2000; Drewry et al., 2000; Harrison et al., 1994) or to a low level of soil compaction (Frost, 1988a). Sometimes also negative effects of loosening on yield are found; these have been ascribed to mechanical damage to sward and roots (Carter and Kunelius, 1998; Frost, 1988a,b).

In the Netherlands, 40% of agricultural land is used as permanent grassland, mainly for dairy farming. Although soil compaction is likely to have negative effects on the productivity of this grassland, little research has been done to assess the effects of amelioration methods. A field experiment by Van Eekeren and Ter Berg (2008) showed (short-lived) positive effects of sward lifting on soil structure, but not on herbage yield. These authors hypothesized that the effectiveness of soil loosening could be enhanced by overseeding (i.e. adding grass seeds to the existing sward), assuming that the rapidly growing roots of seedlings would be more likely to quickly occupy and stabilize the macropores created by soil loosening than the older roots of the existing sward.

The objective of the present study was to explore the potential of sward lifting, with and without overseeding, as a method to ameliorate soil compaction in Dutch grasslands. We tested this method in a compacted permanent grassland, applying it either in spring or in autumn. Effects on soil compaction, soil structure, grass rooting and productivity were measured for up to two growing seasons. We hypothesized that (i) soil loosening by sward lifting would increase herbage yield and N uptake through an improvement of soil structure and rooting conditions; and (ii) overseeding with Italian ryegrass (*Lolium multiflorum* Lam.) would extend the duration of these improvements.

2. Materials and methods

2.1. Site properties

The experiment was conducted in a permanent grassland on a compacted, undrained, fine sandy soil in the southern part of the Netherlands (51°61′N, 5°80′E). This soil was prone to waterlogging throughout the year, after periods of heavy or prolonged rainfall. The soil profile was classified as a Gleyic Podzol and had a 30–40 cm deep A-horizon overlying white sand. Soil properties of the 0–10 cm soil layer were: pH-KCl 5.1, organic matter 4.0%, total C 1.8%, total N 0.157%, P-Al 0.025% and K-HCl 0.004%. Soil properties of the 0–30 cm layer were: pH-KCl 5.0, organic matter 2.9%, total C 1.3%, total N 0.106%, P-Al 0.027% and K − HCl 0.010%. A visual assessment of soil structure and root density, right before start of the experiment, showed that the 0–10 cm soil layer had a good soil structure (high percentage of crumbs), a high root density, a high proportion of young roots and visibly active soil organisms, mainly earthworms of the species *Aporrectodea caliginosa* (see Section 2.4 for the assessment methods). The 10–30 cm soil layer had a moderate to poor soil structure, a high percentage of angular blocky elements, a high proportion of old roots, no visibly active soil organisms and a low number of macropores. The 30–40 cm soil layer showed a poor and compacted soil structure, no root presence, and a low number of visible pores. No roots or worms were found in the white sand below 40 cm depth.

The grass sward was nine years old, contained a mixture of plant species including white clover (*Trifolium repens* L.) and Italian ryegrass (*Lolium multiflorum* Lam.), and was dominated by perennial ryegrass (*Lolium perenne* L.). In previous years, the grass had been managed mostly by cutting (the first four growth periods were cut and the final growth period was grazed by young stock), which involved machine traffic for the application of liquid manure and synthetic fertilizer, and for harvesting. The 30-year average annual rainfall at the site was 804 mm, fairly equally distributed over the year (Royal Netherlands Meteorological Institute KNMI).

2.2. Experimental treatments

The field experiment was designed to assess the effects of a one-time application of soil loosening and/or overseeding on soil structure, grass rooting and productivity. Treatments were applied either in the late spring or early autumn of 2014, and effects were measured in the 2014 and 2015 growing seasons (spring treatments) or the 2015 growing season (autumn treatments). The field experiment was set up as a randomized complete block design, with time of treatment (spring or autumn) assigned to two main plots located adjacent to each other. Within each main plot, all treatments (control, soil loosening, overseeding, and soil loosening combined with overseeding) were replicated on five plots (10 × 2.7 m) in five randomized blocks. Several weeks before applying the treatments (either in spring or in autumn), the sward was sprayed with the herbicide Starane (Dow AgroSciences, Indianapolis, USA) to kill off the white clover in the sward and hence reduce potential variation associated with patchy clover distribution. The spring treatments were applied on 19 May 2014, two weeks after the first regular harvest, and the autumn treatments on 15 September 2014, six days after the fourth regular harvest. Right before applying the treatments, regrowth after the preceding harvest was cut by a flail mower to reduce potential competition between regrowth and seedlings. Overseeding was carried out before soil loosening to avoid re-compaction of the loosened soil, using a Vredo Agri Air slot-seeding machine with a working width of 2.5 m and an inter-row distance of 7.5 cm (Vredo Dodewaard BV, Dodewaard, The Netherlands), sowing Italian ryegrass (*Lolium multiflorum* Lam. cv. Mont Blanc) at 1–2 cm depth and at a rate of 25 kg ha^{-1}. Soil loosening was carried out with an Evers Agro sward lifter with five shanks, spaced 60 cm apart and fitted with hardened, 20 cm wide winged tines (Evers Agro BV, Almelo, The Netherlands). With this machine, that operated to a depth of 25 cm, the entire top layer (0–25 cm, soil and sward) was lifted 10–15 cm upwards and then lowered again.

Soil moisture content at the time of treatment application was an estimated 85% and 75% of field capacity in spring and autumn, respectively, and cumulative rainfall within 10 days after treatment was 10 and 30 mm, respectively. Thus, conditions were optimal for soil loosening (cf. Burgess et al., 2000). After treatment applications, the trafficking was controlled. Plots were trafficked lengthwise by a tractor carrying a small-scale fertilizer spreader (three to four times each growing season, wheel distance 1.5 m) and a Haldrup grass harvester (four to five times each growing season, wheel distance 0.9 m), in order to apply fertilization and determine herbage yield (see Sections 2.3, 2.5). Additionally, there was regular (light) machine traffic for grass raking, which passed over the experiment lengthwise (i.e. all plots were affected equally), four times each growing season. Traffic after treatment application, however, only had a minimal effect on re-compaction (see Sections 3.1, 4.1).

2.3. Grassland fertilization

The experiment covered four growth periods in the 2014 growing season and five growth periods in the 2015 season. In the experimental period, all N fertilizer was applied as synthetic fertilizer calcium ammonium nitrate (CAN, 27% N). In 2014, the plots with spring treatment received N fertilizer in the three growth periods following treatment at a rate of 60, 50 and 30 kg N ha^{-1}, respectively, leaving the last growth period of the season unfertilized. The plots with autumn treatment did not receive N fertilizer in the growth period following treatment, also leaving the last growth period unfertilized. In 2015, all plots (spring and autumn treatments) received N fertilizer in the first four growth periods at a rate of 90, 70, 60 and 50 kg N ha^{-1} respectively; and K fertilizer (KCl, 50% K) in the first three growth periods at a rate of 100, 83 and 66 kg K ha^{-1}, respectively. Phosphorus fertilizer was not applied, given the high P-status of the soil. All fertilizers were evenly distributed over each plot with a custom-made, small-scale fertilizer spreader (Europart, Austria). In 2014, fertilizer was applied on May 8, June 19 and August 4, and in 2015 on March 19, May 19, June 23 and August 6.

2.4. Soil measurements

Soil measurements consisted of penetration resistance, root biomass, and a visual assessment of soil structure and rooting. Soil penetration resistance was measured 1, 4 and 10 months after spring treatments (June and September 2014, March 2015), and 2, 6 and 12 months after autumn treatments (November 2014, March and September 2015). Penetration resistance was measured with a penetrologger (cone area 1 cm^2, apex angle 60°; Eijkelkamp, The Netherlands) at 1-cm depth intervals to 40 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 water content of the soil profile was near field capacity during measurements in November 2014 and March 2015, providing optimal conditions for penetration resistance measurements (cf. Smith et al., 1997). On the other observation dates, conditions were drier but still allowed reliable measurement of differences between treatments.

Root biomass was sampled 1 and 4 months after spring treatments (June and September 2014), and 6 and 12 months after autumn treatments (March and September 2015). 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 depth) 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 removed by hand and samples were oven-dried at 70 °C for 24 h to determine root dry weight and calculate root biomass per hectare. In March 2015, the 30–40 cm soil layer was not sampled because the water table was too high.

Visual assessment of soil structure and rooting took place 1, 4 and 10 months after spring treatments (June and September 2014, March 2015), and 6 and 10 months after autumn treatments (March and July 2015). Only the control and the loosening-only plots were assessed, except in July 2015, when all plots were assessed. Assessments were conducted by an expert, on 20 × 20/25 cm soil cubes from the 0–25 cm and 25–45 cm soil layer. 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, sub-angular 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.

2.5. Sward measurements

Sward measurements consisted 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 central area (15 m^2) of each plot. In 2014, the plots were harvested on June 16, July 30, September 10 and November 17 (where June 16 was the second harvest of 2014 but the first harvest of the experiment), and in 2015 on May 15, June 15, July 30, September 14 and October 27. The harvested material was weighed and samples were oven-dried at 70 °C for 48 h to determine dry weight and calculate herbage biomass and N uptake. Total N content in the dried samples was determined by a Dumas-based method (NEN 16634-1, 2008). In 2014, total N content was determined only in samples from the control and loosening-only plots.

The assessment of sward botanical composition 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. The assessment was carried out 4 and 13 months after spring treatments (September 2014 and June 2015) and 9 months after autumn treatments (June 2015). After 13 months (spring treatments), only the control and loosening-only plots were assessed.

2.6. Statistical analysis

Treatment effects were statistically analyzed for each of the two main plots separately, using the ANOVA-procedure in the Genstat statistical package (17th edition). Soil penetration resistance was analyzed per 10 cm soil layer, based on the average of ten (1-cm increment) observations per layer. Root biomass was analyzed per 10 cm soil layer and for all soil layers combined. Soil structure and root density were analyzed per 0–25 cm and 25–45 cm layer. Herbage yield and N uptake were analyzed per individual harvest as well as cumulative harvest per growing season. Here, results are discussed in the order of the main effects (soil loosening, overseeding) followed by the interaction (soil loosening combined with overseeding). When a main effect is discussed, e.g. that of soil loosening, the average effect of the treatments with soil loosening (loosening only, loosening combined with overseeding) is compared to the average effect of the treatments without loosening (control, overseeding-only), the controls. When the interaction is discussed, the effect of the combined treatments is compared to the other treatments (control, loosening-only, overseeding-only).

3. Results

3.1. Soil penetration resistance

Soil loosening in spring reduced soil penetration resistance for at least 10 months (last observation), compared to the controls (Fig. 1). Resistance was significantly lower ($P < 0.01$) down to 40 cm depth after 1 and 4 months, and down to 30 cm depth after 10 months ($P < 0.01$). When applied in autumn, soil loosening reduced penetration resistance for at least 12 months (last observation), compared to the controls (Fig. 1). Here, resistance was significantly lower ($P < 0.01$) down to 40 cm depth after 2 and 6 months, and down to 30 cm depth after 12 months ($P = 0.02$). In both spring and autumn treatments, the positive effect of soil loosening on penetration resistance lessened over time.

Overseeding in spring increased ($P < 0.01$) penetration resistance in the 10–20 cm soil layer after 10 months, compared to the controls (Fig. 1). When applied in autumn, overseeding increased ($P = 0.04$) penetration resistance down to 40 cm depth after 6 months, but no difference ($P > 0.10$) was found after 12 months.

The combination of soil loosening and overseeding did not have a different effect ($P > 0.10$) on penetration resistance, when compared to soil loosening-only or overseeding-only, although on some observation dates the penetration resistance in the 10–20/25 cm layer appeared to increase slightly for the combined treatments compared to loosening-only (Fig. 1).

The sward lifter not only affected soil penetration resistance down to its working depth (25 cm), but also 10–15 cm deeper, for a total depth of up to 40 cm (Fig. 1).

3.2. Root biomass

Soil loosening in spring had no effect ($P > 0.10$) on total root biomass (0–40 cm depth) or root biomass per 10 cm soil layer, measured after 1 and 4 months (Fig. 2). When applied in autumn, soil loosening also had no effect on total root biomass, as measured after 6 and 12 months. However, after 12 months, root biomass was higher in the 10–20 cm and 20–30 cm soil layers ($P = 0.02$ and $P = 0.01$,

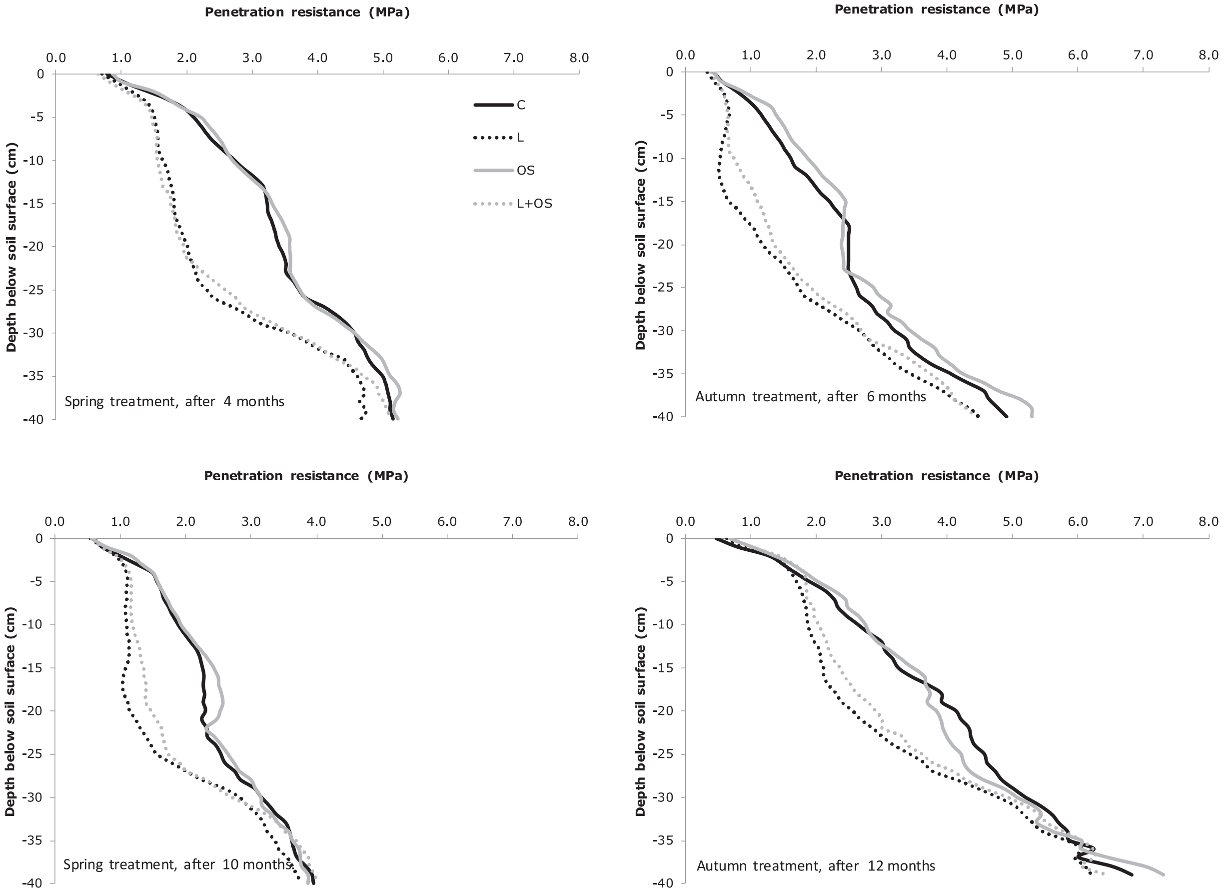

Fig. 1. Penetration resistance (MPa) in the 0–40 cm soil profile of a compacted grassland, as influenced by sward lifting (L) and/or overseeding (OS) applied in the spring or autumn of 2014, compared to the untreated control (C) (n = 5). Measurements were done 4 and 10 months after spring treatment and 6 and 12 months after autumn treatment.

respectively) of the loosened plots, compared to the controls. At this time, average root biomass in the 10–20 cm soil layer was 433 and 560 kg dry matter (DM) ha^{-1} in the controls and loosening treatments, respectively; and root biomass in the 20–30 cm soil layer was 213 kg and 323 kg DM ha^{-1}, respectively.

Overseeding in spring increased ($P = 0.03$) root biomass in the 20–30 cm layer from 77 to 125 kg DM ha^{-1} after 4 months, whereas overseeding in autumn had no effect ($P > 0.10$) on root biomass in any of the soil layers measured (Fig. 2).

The combination of soil loosening and overseeding did not have a different effect ($P > 0.10$) on root biomass, when compared to soil loosening-only or overseeding-only, neither in the spring nor autumn treatments (Fig. 2).

3.3. Soil structure and root density

Soil loosening in spring had a positive effect on soil structure in the 0–25 cm soil layer for at least 10 months (last observation), with the largest effect observed after 1 month. Compared to the control, loosening in spring increased the proportion of crumbs measured after 1, 4 and 10 months, from 9% to 42%, 10% to 25%, and 12% to 19%, respectively ($P = 0.03$, $P = 0.02$ and $P = 0.03$, respectively); and decreased the proportion of angular blocky elements from 74% to 22%, 73% to 43% and 78% to 34%, respectively ($P < 0.01$, $P < 0.01$ and $P = 0.03$, respectively). Root density in the 0–25 cm soil layer was also positively influenced. Compared to the control, loosening in spring increased the scores for total root density and proportion of young roots as observed after 1 month ($P < 0.01$ and $P < 0.01$, respectively) and after 4 months ($P = 0.05$ and $P = 0.02$, respectively), but this effect had disappeared ($P > 0.10$) after 10 months (Fig. 3). Soil loosening in spring had no significant effect ($P > 0.10$) on soil structure and root density in the 25–45 cm soil layer.

When applied in autumn, soil loosening also had a positive effect on soil structure in the 0–25 cm soil layer for at least 10 months (last observation). Compared to the control, loosening increased the proportion of crumbs after 6 and 10 months, from 15% to 50% and from 10% to 54%, respectively ($P = 0.05$ and $P < 0.01$, respectively), and decreased the proportion of angular blocky elements from 68% to 12% and from 74% to 15%, respectively ($P < 0.01$ and $P = 0.02$, respectively). Root density in the 0–25 cm soil layer was also positively influenced. Compared to the control, loosening in autumn increased the scores for total root density and proportion of young roots as observed after 6 months ($P < 0.01$ and $P < 0.01$, respectively), and the score for total root density after 10 months ($P < 0.01$) (at that time, no young roots were present due to drought) (Fig. 3). As for the 25–45 cm layer, no effects of soil loosening in autumn were found on root density, but some effects were found on soil structure: compared to the control, the proportion of sub-angular blocky elements had increased ($P = 0.01$) after 10 months, from 10% to 18%, while the proportion of angular blocky elements had decreased ($P = 0.01$) from 90 to 82% at that time.

Overseeding in autumn had no significant effects ($P > 0.10$) on soil structure or root density after 10 months (the only observation date). The combination of soil loosening and overseeding in autumn did not have a positive effect on the proportion of crumbs and total root density in the 0–25 cm soil layer, in contrast with the positive effect of the loosening-only treatment, compared to the control ($P < 0.01$).

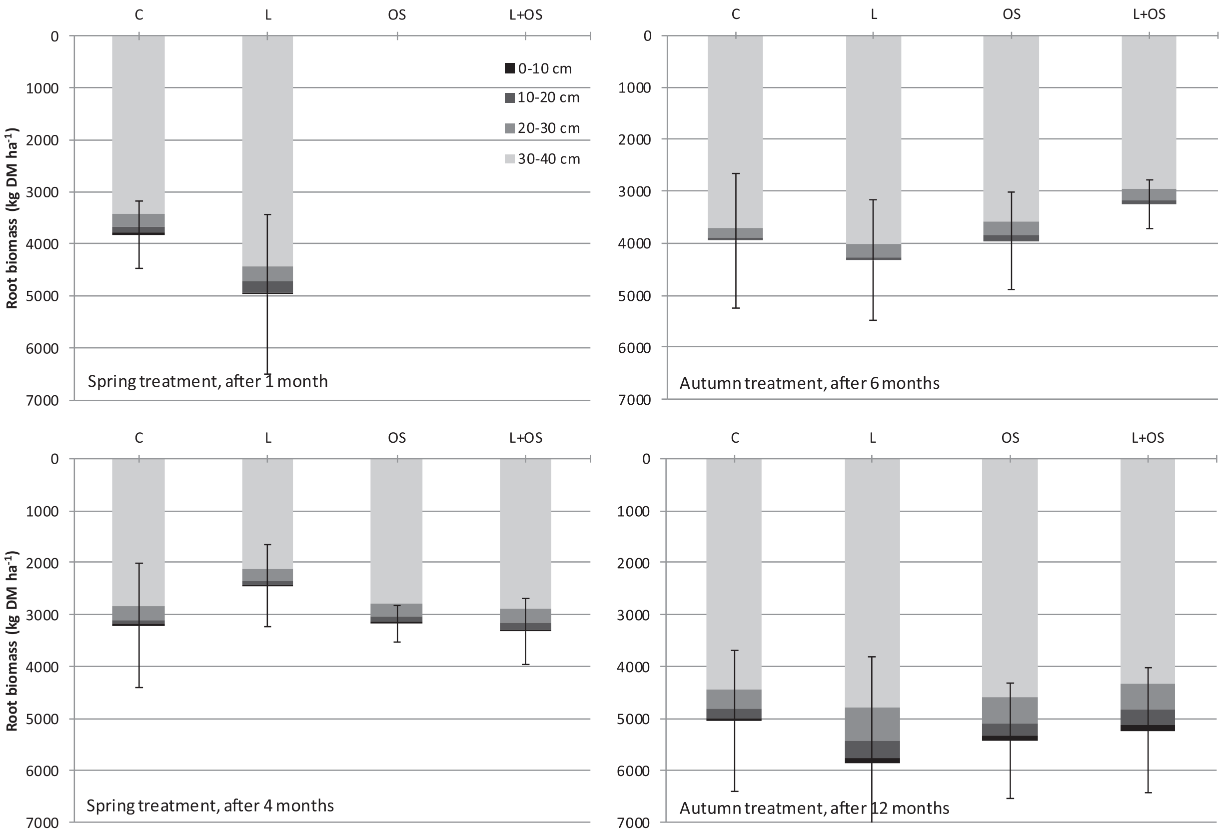

Fig. 2. Root biomass (kg DM ha^{-1}) in the 0–10, 10–20, 20–30 and 30–40 cm soil layers of a compacted grassland, as influenced by sward lifting (L) and/or overseeding (OS) applied in the spring or autumn of 2014, compared to the untreated control (C) (n = 5). Root biomass was measured 1 and 4 months after spring treatment and 6 and 12 months after autumn treatment. Error bars represent 2 x standard errors of total root biomass (0–40 cm soil layer). Root biomass in treatment OS and L + OS was not measured 1 month after spring treatment; root biomass in the 30–40 cm layer could not be measured 6 months after autumn treatment, due to the high water table at that time.

3.4. Herbage dry matter yield

Soil loosening in spring had a significant effect ($P < 0.05$) on herbage yield of each of the four growth periods in the first growing season (2014): while yield of the first growth period was lower, yields of the second, third and fourth growth periods were higher, compared to the controls (Table 1). However, cumulative yield of the first year was not influenced ($P > 0.10$). In the second growing season (2015), no effect of loosening was observed on yield of the first, second and third growth periods, but yields of the fourth and fifth growth periods were lower ($P < 0.01$), and cumulative yield tended to be lower ($P = 0.10$) in the loosened plots, compared to the controls.

When applied in autumn, soil loosening significantly increased ($P < 0.01$) the yield of the first following growth period (2015 growing season), but had no significant effect ($P > 0.10$) on subsequent growth periods (Table 1). Cumulative yield tended to be higher ($P = 0.09$) in the loosened plots, compared to the controls.

Overseeding in spring decreased ($P < 0.01$) the yield of the first following growth period but did not influence ($P > 0.10$) later growth periods of that year (2014), compared to the controls. Cumulative yield of the first year tended to be lower ($P = 0.09$). In the second year (2015), yield of the first growth period was higher ($P = 0.02$), while later growth periods were not influenced; nonetheless, cumulative yield was higher ($P < 0.01$). When applied in autumn, overseeding tended to increase ($P = 0.07$) yield of the fourth growth period of the following year, but did not influence yield of other growth periods nor cumulative yield of that year.

The combination of soil loosening and overseeding, when applied in spring, did not have different effects ($P > 0.10$) on the yield of any of the growth periods in the two growing seasons following treatment, when compared to the effects of loosening-only or overseeding-only. When applied in autumn, soil loosening combined with overseeding tended to increase ($P = 0.09$) the yield of the third growth period of 2015, compared to loosening-only, and reduced ($P = 0.04$) yield of the fifth growth period, compared to overseeding-only. The cumulative yield in 2015 was, however, not influenced ($P > 0.10$).

3.5. Herbage nitrogen uptake

Soil loosening in spring decreased N uptake in the first following growth period (although this effect was not significant, $P = 0.19$), but tended to increase or increased N uptake in the next three periods, compared to the controls ($P = 0.07$, $P = 0.01$ and $P = 0.07$, respectively) (Table 2). However, cumulative N uptake during this first year (2014) was not significantly influenced ($P > 0.10$). In the second year (2015), N uptake tended to be higher ($P = 0.08$) in the first growth period, but was lower ($P < 0.01$) in the fourth growth period and tended to be lower ($P = 0.06$) in the fifth growth period. Cumulative N uptake in the second year was not influenced ($P > 0.10$).

When applied in autumn, soil loosening increased ($P = 0.02$) N uptake in the first following growth period (in 2015), compared to the controls. However, N uptake in the next four growth periods was not different ($P > 0.10$) from the controls, and no effect was observed ($P > 0.10$) on cumulative N uptake.

Overseeding in spring increased ($P = 0.02$) N uptake in the first growth period of the second year (first year not measured) and cumulative N uptake of that year ($P = 0.04$), compared to the controls. When applied in autumn, overseeding tended to increase ($P < 0.10$) N uptake in the first two growth periods of the following year (2015) and increased ($P = 0.03$) cumulative N uptake in that year.

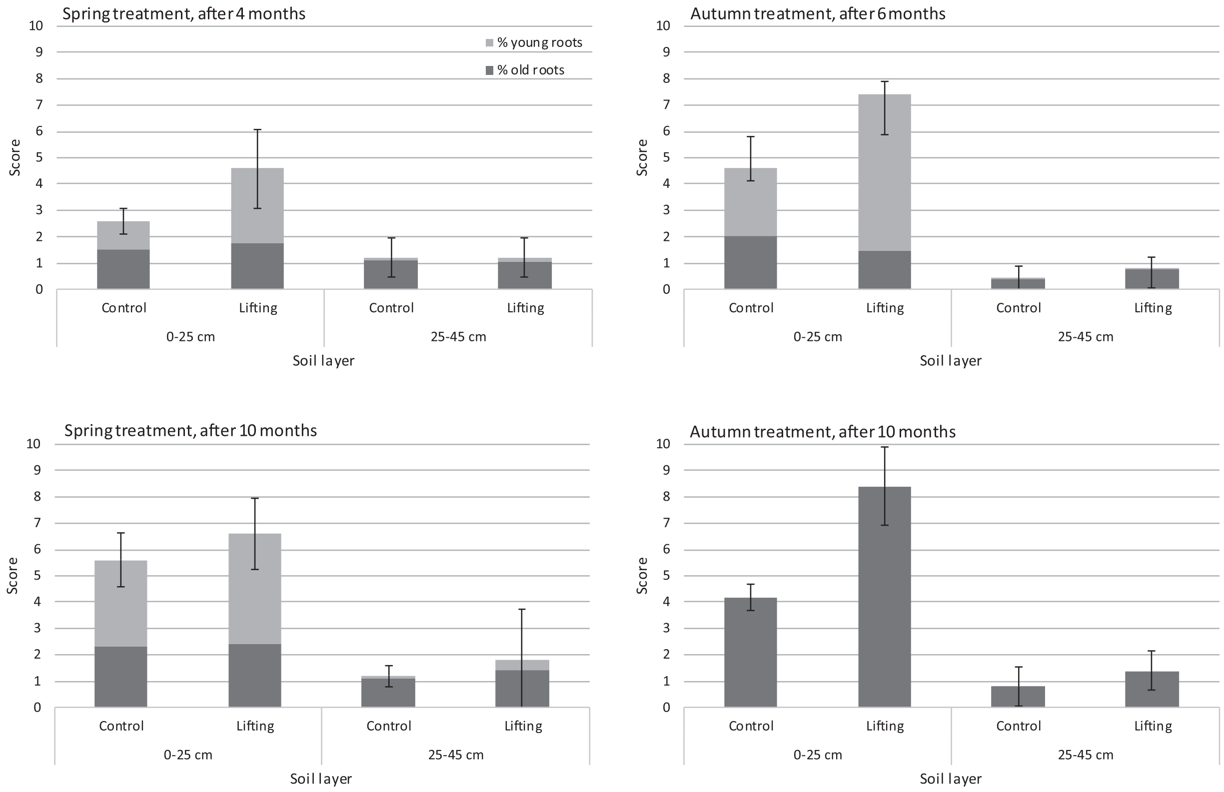

Fig. 3. Root density (score 1–10) and estimated proportion (%) of young versus old roots in the 0–25 and 25–45 cm soil layers of a compacted grassland, as influenced by sward lifting applied in the spring or autumn of 2014 (n = 5). Measurements were done 4 and 10 months after spring treatment and 6 and 10 months after autumn treatment. Error bars represent 2 x standard errors of the root density score within time of measurement and soil layer. Young roots were not present in the 25–45 cm and 0–45 cm soil layer, 6 months and 10 months after autumn treatment, respectively.

The combination of soil loosening and overseeding, when applied in spring, increased (P = 0.02) N uptake in the first growth period of the second year (first year not measured), compared to all other treatments, and tended to increase (P = 0.09) cumulative N uptake in that year, compared to the loosening-only treatment. When applied in autumn, soil loosening combined with overseeding tended to increase (P = 0.06) N uptake in the first growth period of the following year, compared to all other treatments, and decreased (P = 0.01) N uptake in the fifth growth period, compared to overseeding-only. Cumulative N uptake was not influenced (P > 0.10).

3.6. Sward botanical composition

Soil loosening in spring had no effect (P > 0.10) on total sward soil cover as observed after 4 months (94% on average), but decreased (P = 0.03) the relative abundance of L. *perenne* from 68% to 63%,

Table 1
Herbage yield (kg DM ha^{-1}) of a compacted grassland, as influenced by sward lifting and/or overseeding applied in the spring or autumn of 2014 (n = 5).

Time of treatment	Year	Harvest #	Treatment[a]				P-value[b]		
			C	L	OS	L + OS	L	OS	L + OS
Spring 2014	2014	1	2869	2089	2306	1711	< 0.01	< 0.01	0.47
		2	2607	2753	2674	2841	0.01	0.18	0.85
		3	2344	2571	2369	2563	< 0.01	0.88	0.77
		4	1124	1190	1069	1311	0.02	0.57	0.15
		Total	8944	8603	8417	8426	0.40	0.09	0.37
	2015	1	4584	4524	4759	4881	0.75	0.02	0.35
		2	2729	2766	2814	2909	0.38	0.14	0.70
		3	1724	1646	1808	1705	0.22	0.32	0.85
		4	1475	1294	1485	1282	< 0.01	0.97	0.71
		5	939	848	970	896	< 0.01	0.16	0.75
		Total	11451	11078	11836	11673	0.10	< 0.01	0.49
Autumn 2014	2015	1	4648	5002	4434	5231	< 0.01	0.97	0.23
		2	2534	2446	2666	2500	0.27	0.41	0.73
		3	1721	1650	1699	1795	0.79	0.20	0.09
		4	1507	1557	1596	1620	0.36	0.07	0.75
		5	822	868	899	816	0.52	0.65	0.04
		Total	11232	11523	11294	11962	0.09	0.36	0.48

[a] C = control; L = lifting; OS = overseeding.

[b] P-values of the main effect for L and OS and of the interaction for L + OS. A difference is significant where P < 0.05.

Table 2
Nitrogen uptake (kg N ha^{-1}) in a compacted grassland, as influenced by sward lifting and/or overseeding applied in the spring or autumn of 2014 ($n = 5$).

Time of treatment	Year	Harvest #	Treatment[a]				P-value[b]		
			C	L	OS	L + OS	L	OS	L + OS
Spring 2014	2014	1	58	48	-[c]	–	0.19	–	–
		2	69	76	–	–	0.07	–	–
		3	54	65	–	–	0.01	–	–
		4	36	40	–	–	0.07	–	–
		Total	217	230	–	–	0.16	–	–
	2015	1	78	76	77	86	0.08	0.02	0.02
		2	66	66	67	72	0.26	0.11	0.30
		3	50	46	50	48	0.20	0.62	0.77
		4	55	48	54	48	< 0.01	0.93	0.64
		5	27	25	28	26	0.06	0.27	0.90
		Total	275	261	277	280	0.23	0.04	0.09
Autumn 2014	2015	1	76	79	76	96	0.02	0.07	0.06
		2	61	61	68	64	0.44	0.07	0.44
		3	52	51	50	51	0.95	0.64	0.65
		4	54	57	57	58	0.34	0.23	0.55
		5	22	24	25	23	0.63	0.52	0.01
		Total	265	272	277	292	0.14	0.03	0.56

[a] C = control; L = lifting; OS = overseeding.

[b] P-values of the main effect for L and OS and of the interaction for L + OS. A difference is significant where $P < 0.05$.

[c] Not determined.

increased ($P = 0.01$) the relative abundance of L. *multiflorum* from 5% to 11%, and tended to decrease ($P = 0.06$) the relative abundance of *Poa annua* L. from 10% to 9%, compared to the controls. The relative abundances of other species present, *Poa trivialis* L. (14%), *Taraxacum officinale* L. (3%) and *Phleum pratense* L. (1%), were not affected. After 13 months (second and last observation), sward cover and relative species abundances were not different ($P > 0.10$) between the loosening-only and control treatment. Sward cover was on average 95%, and relative abundances of *L. perenne* and *L. multiflorum* were 59% and 12%, respectively. When applied in autumn, soil loosening had no effect ($P > 0.10$) on sward cover (95% on average) after 9 months (first and only observation), but tended to increase ($P = 0.06$) the relative abundance of *L. multiflorum* in the sward from 11% to 14%, compared to the controls. The relative abundances of other species were not affected ($P > 0.10$).

Overseeding in spring tended to increase ($P = 0.06$) the relative abundance of the overseeded species, *L. multiflorum*, from 6% to 10% after 3 months, without significantly affecting ($P > 0.10$) the relative abundances of other species, compared to the controls. When applied in autumn, overseeding tended to increase ($P = 0.06$) the relative abundance of *P. trivialis* from 10% to 13% after 9 months, compared to the controls.

The combination of soil loosening and overseeding, when applied in spring, decreased ($P = 0.02$) the relative abundance of *Poa annua* after 4 months to 7%, compared to 10% in the other treatments. Relative abundances of other species, including the overseeded species (*L. multiflorum*), were not affected ($P > 0.10$). When applied in autumn, soil loosening combined with overseeding tended to increase ($P = 0.06$) the relative abundance of *L. multiflorum* to 15% after 9 months (first and only observation), compared to 11% in the other treatments.

Soil loosening by sward lifting did not result in a deterioration of the sward botanical composition, i.e. in a lower soil cover, a decline in the relative abundance of *L. perenne*, or an increase in the relative abundance of unwanted species.

4. Discussion

4.1. Effects of soil loosening

Soil loosening by sward lifting, whether applied in spring or in autumn, improved the topsoil structure for at least 10–12 months (last observations), as measured by decreased soil penetration resistance and increased soil crumbliness, total root density and density of young roots. However, these improvements did not translate into a consistent or lasting increase in herbage yield or N uptake, measured over up to two growing seasons.

When applied in spring, soil loosening initially caused a decrease in herbage yield and N uptake, which was likely the result of damage to the root system (Burgess et al., 2000; Carter and Kunelius, 1998). Root damage, e.g. by pruning or severing, can result in a temporary higher growth rate of roots relative to shoots and the partitioning of extra C and N towards roots, at the expense of shoot growth (Wilson, 1988). In our experiment, the initially lower herbage yield and N uptake was followed by higher yields and N uptake during the remainder of the 2014 growing season (Tables 1,2), which was likely due to a re-balancing of shoot-root ratios (Ennik and Baan Hofman, 1983; Wilson, 1988) and re-distribution of N from roots to shoots (Ourry et al., 1988, 1990). Nonetheless, the initial reduction in herbage yield following soil loosening in spring was not fully compensated in later growth periods, neither in the first nor in the second growing season.

In contrast to soil loosening in spring, soil loosening in autumn tended to increase cumulative herbage yield in the following growing season (2015). Soil structure, as observed from the increase in crumbliness, was also more improved, compared to the increase after spring treatment. These results support the view that soil loosening should be carried out in autumn rather than in spring (Bhogal et al., 2011; Burgess et al., 2000). However, the positive effect of autumn soil loosening on herbage yield and N uptake was significant only in the first growth period after loosening (Table 2). This effect may be explained by a (short-lived) increase of soil organic N mineralization due to soil loosening (Kristensen et al., 2003).

A similar stimulation of N mineralization likely also occurred after soil loosening in spring, where its positive effect on herbage N uptake, initially masked by the negative effects of root and sward damage, became apparent in later growth periods of that year (Table 2). However, in the second growing season, N uptake in the soil loosening treatments was lower rather than higher, and the difference became significant in the fourth and fifth growth period. Eventually, cumulative N uptake over two growing seasons was not different between the control (492 kg N ha^{-1}) and loosening-only treatment (491 kg N ha^{-1}) (Table 2). These results support the postulation by Grace et al. (1993) that an initial depletion of the labile N pool in grassland soil may, later on, result in lower N mineralization from the more resistant N pool. In the present experiment, the reversal of effects of loosening on N uptake only became visible during the second half of the second growing season, which stresses the need for longer duration of grassland field experiments where treatments may affect soil N dynamics.

Apart from the positive effect of soil loosening on herbage yield and N uptake in the first growth period of the season following autumn treatment, we did not find a lasting increase in herbage yield, despite the improved soil structure and rooting. A lack of (significant) effects of soil loosening on herbage yield was also reported by Burgess et al. (2000); Drewry et al. (2000) and Harrison et al. (1994), whereas actual yield decreases were reported by Carter and Kunelius (1998) and Frost (1988a,b). In contrast, Bhogal et al. (2011) and McConnell and Evans (2015) reported annual yield increases of up to 1800 kg DM ha^{-1} or 14% after sward lifting, but these studies were limited to one growing season. In the experiment by McConnell and Evans (2015), pasture yield was measured indirectly using a rising plate meter, which may have influenced the accuracy of the results.

When analyzing the results from the present and published experiments, a key question is whether the initial level of soil compaction was severe enough to expect a positive effect of soil loosening on herbage yield. If the topsoil is not or only moderately compacted, the positive effect is likely to be outweighed by the negative effects of sward and root damage caused by soil loosening (Bhogal et al., 2011; Frost, 1988a,b). Carter and Kunelius (1998), who found a negative yield response after non-inversion loosening, reported that the sandy loam in their experiment was in a state of “incipient compaction”; the average penetration resistance in the 5–25 cm wet soil profile, before soil loosening, was 1.85–1.90 MPa. In our experiment, the average penetration resistance in the 5–25 cm wet soil profile of the control treatment varied between 2.08 and 2.14 MPa, based on measurements in November 2014 and March 2015 when soil moisture content was near field capacity (i.e. optimal for penetration resistance measurement, cf. Smith et al., 1997). Using the values of Carter and Kunelius (1998) as a reference, the sandy soil in our experiment was moderately (rather than severely) compacted. While soil loosening reduced the average penetration resistance, measured in the same soil layer under the same conditions, from 2.08 to 2.14 to 0.92–1.17 MPa, the lack of severe compaction may explain why we did not find a consistent or lasting increase in herbage yield.

4.2. Effects of overseeding

Overseeding was only slightly effective to increase the relative abundance of the overseeded species, *L. multiflorum*, in the sward, and loosening was at least as effective. The combination of loosening and overseeding resulted in higher relative abundance of *L. multiflorum* compared to loosening-only or overseeding-only, although this difference only tended to be significant after autumn treatment. Overseeding in both spring and autumn increased N uptake of the first growth period in 2015 only significantly when combined with soil loosening (Table 2). A denser rooting of *L. multiflorum* in the loosened soil could have enabled this species to absorb more N at depth, compared to *L. perenne* (Popay and Crush, 2009). Also, N uptake during the preceding winter (from N mineralized due to loosening) could have been higher for *L. multiflorum* compared to *L. perenne*, due to a higher root metabolic activity of *L. multiflorum* at low temperatures (Malcolm et al., 2014).

The effects of overseeding on herbage yield were variable. In the spring treatments, the lower herbage yield of the first growth period after overseeding can be explained by the damaging effect of the cutting discs of the slot-seeding machine to the sward and roots, while the higher cumulative herbage yield of the following season (2015) was mainly due to a significant positive effect on the first growth period of that year, resulting from a higher N uptake. For the treatments with overseeding in autumn, the tendency to a higher herbage yield of the fourth growth period in 2015 remains unexplained; it was not the result of a higher N uptake.

In contrast to our hypothesis, the combination of soil loosening and overseeding did not extend the positive effects of soil loosening on soil structure, root density or grass productivity. After overseeding, it takes about one week for ryegrass seeds to germinate (Shen et al., 2008) and an additional two to three weeks for the roots to arrive at 25 cm depth, at an average root depth penetration rate of 0.8–1.1 mm d^{-1} °C^{-1} (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2001) and at an estimated average air temperature of 15 °C. In our experiment, root biomass of the existing sward across the 0–40 cm soil layer was relatively high, compared to what has been found in grassland experiments on other sandy soils in the region (De Boer et al., 2016; Van Eekeren et al., 2010), and included roots growing at depth (Fig. 2). Therefore, new root growth from the existing sward was likely effective enough to occupy the pores created by soil loosening in this experiment, leaving no room for an additional effect of overseeding.

5. Conclusions

The positive effects of sward lifting on soil structure and rooting in the compacted grassland of our study persisted over two growing seasons, but did not result in consistent or lasting herbage yield increases. This appears to be because the soil at our site was only moderately compacted; a positive yield response to soil loosening is more likely to occur in more severely compacted soils. Future research should therefore focus on severely compacted soils, to better identify the potential effects of soil loosening on grass productivity and to determine a 'compaction threshold above which soil loosening increases yield. Our results indicate that soil loosening experiments should measure not only herbage yield but also herbage N uptake. Differences in longer-term N uptake patterns enable to distinguish whether yield increases are caused by temporary increased N mineralization, or by other factors, such as improved root growth. Furthermore, our results indicate that grassland experiments in which soil N dynamics are influenced should run for at least two growing seasons, to account for potential compensatory effects or reversal of effects after the first growing season. Lastly, our study showed that complementary overseeding did not extend the duration of soil loosening effects. Apparently, new root growth from the existing sward was effective enough to stabilize these effects.

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