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Blade Aeration Effects on Near-Surface Permeability and Overland Flow Likelihood on Two Stagnosol Pastures in Cumbria, UK

Ethan E. Wallace* and Nick A. Chappell

Abstract

Overland flow (OF) from permanent pastures is believed to be a rapid pathway to the drainage network and potentially contributes to flooding within numerous grassland regions of the world. Studies investigating whether aeration can reduce observed OF have revealed mixed findings. To improve process interpretation within these studies, topsoil saturated hydraulic conductivity (K_s) and penetration resistance (PR) were measured at two permanent Stagnosol (Aquic soil) pastures (P1 and P2) within Cumbria, UK, after blade aeration to 10 cm. Results were measured 2, 6, 13, and 21 wk post-aeration and compared with the local rainfall record to assess the impact on infiltration excess overland flow (IEOF) likelihood (when rainfall intensity exceeds soil infiltration capacity). Within P1, aeration significantly increased K_s by up to a factor of 7.5 and caused several significant reductions in PR between 5 and 15 cm. Aeration decreased the IEOF likelihood during the 13- and 21-wk sampling dates, reducing IEOF likelihood from up to 11.4% of rainfall periods pre-aeration to 0.0926% of rainfall periods post-aeration. Aeration within P2 revealed no significant increases in K_s, and no PR change besides a significant increase at 10 cm. The IEOF likelihood was virtually identical between aerated and unaerated treatments within P2. The study highlights that aeration can significantly improve K_s and PR, as well as substantially reduce the likelihood of IEOF generation, although benefits can be site specific.

Core Ideas

- Aeration can significantly increase topsoil permeability and reduce compaction.
- Aeration can substantially lower the likelihood of infiltration excess overland flow.
- Aeration may be ineffective on impermeable subsoils or highly compacted sites.
- Ex situ permeability results may have limited application within aeration research.
- Combined BACI and paired-plot approaches are advised for future aeration studies.

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*Corresponding author (e.wallace@lancaster.ac.uk).

Extensive soil compaction is hypothesized to increase flood risk across numerous regions of the globe (Alaoui et al., 2018). Within the United Kingdom, 60% of managed pasture in England and Wales exhibits signs of topsoil compaction and/or surface capping (AHDB, 2016). Topsoil compaction can severely impede water infiltration and drainage due to reduced soil pore volumes, thereby altering the distribution, frequency, and continuity of water-transmitting macropores within the soil matrix (Kuncoro et al., 2014). This pore network restructuring can increase the likelihood of infiltration excess overland flow (IEOF) during precipitation events. Infiltration excess overland flow is generated when rainfall intensity exceeds soil infiltration capacity. Infiltration capacity is the flow of water into saturated soil under unit cross-sectional area and unit hydraulic gradient. Infiltration excess overland flow is often a rapid drainage pathway and increases the likelihood of channel capacity being exceeded, creating flooding (see Horton, 1933).

Topsoil compaction reduces pasture productivity by restricting sward root aeration (Davies et al., 1989; Douglas et al., 1995). This compaction is often caused by livestock grazing in wet conditions (see Drewry et al., 2000a), as well as by farm traffic (see Bhogal et al., 2011). Slit aeration to 10 to 15 cm using a blade aerator is a practice commonly adopted by UK livestock farmers to aerate pasture for increased sward production (Davies et al., 1989; Bhogal et al., 2011). This practice has the potential co-benefit of enhancing topsoil permeability (Davies et al., 1989; Crawford and Douglas, 1993; Douglas et al., 1995). Enhanced permeability (infiltration capacity) within pastures can potentially minimize IEOF, thus reducing the fast drainage pathway (O'Connell et al., 2007), alongside reducing agrochemical losses carried within surface flows (Van Vliet et al., 2006).

Mechanical slit aeration (blades or tines) has been paired with changes in overland flow (OF) within the United States (Shah et al., 2004; Franklin et al., 2006, 2007; Butler et al., 2008; De Koff et al., 2011) and Canada (Van Vliet et al., 2006) with mixed results (Table 1). Shah et al. (2004) found aeration did not significantly reduce rainfall-induced OF, although significant reductions were found when combined with liquid dairy manure application. Franklin et al. (2006) found no significant OF reductions after aeration when incorporating inorganic

Lancaster Environmental Centre, Lancaster Univ., Lancaster, LA1 4YQ, UK. Assigned to Associate Editor Ray Anderson.

Abbreviations: BACI, before–after–control–impact; IEOF, infiltration excess overland flow; MWW, Mann–Whitney–Wilcoxon; MORI, maximum observed rainfall intensity; OM, organic matter; OF, overland flow; P1, Field Pasture 1; P2, Field Pasture 2; PR, soil penetration resistance.

fertilizers and broiler litter. Van Vliet et al. (2006) found that annual winter OF from aerated plots significantly decreased by 47 to 81% compared with unaerated plots over a 4-yr study in British Columbia, Canada. Franklin et al. (2007) found that aeration significantly reduced OF, although effects were soil dependent. Butler et al. (2008) found that aeration failed to significantly alter OF under natural soil conditions, after various fertilizer application methods, and after artificial compaction. De Koff et al. (2011) highlight aeration to occasionally decrease OF volumes significantly, with some significant increases in infiltration rate (based on subtracting OF from rainfall). These conflicting findings highlight the need for a greater understanding of the processes governing OF generation after slit aeration. No research directly examines how slit aeration alters topsoil permeability (infiltration capacity), which is the pivotal IEOF controlling parameter. This study addresses this key evidence gap at two nearby pastures, having a soil type that is considered highly susceptible to compaction, restricted aeration, and OF, namely, a Clifton Association Stagnosol.

The objectives of this study were (i) to ascertain if blade aeration reduces soil penetration resistance (PR) and increases topsoil permeability in two nearby FAO Stagnosol permanent pasture replicates; and (ii) to assess blade aeration effects on the likelihood of IEOF generation by comparing statistical distributions of topsoil permeability with 847,320 values that comprise a 25-yr record of 15-min observed local rainfall intensity.

Materials and Methods

Study Site

Measurements were taken within two reseeded permanent pastures dominated by perennial ryegrass (*Lolium* spp.), situated 9 km north of Penrith in Cumbria, UK, between June and November 2018. The local climate is wet temperate, with a mean winter temperature of 4.9°C and a mean summer temperature of 12.1°C (Met Office, 2016). The 1990 to 2018 average annual rainfall is 1050 mm at Skelton, located 4.5 km southwest of the experimental site.

The experimental site has plots within two nearby fields (Field P1 and Field P2, Fig. 1). The center of the P1 plot is ∼600 m from the center of the P2 plot (54°44′00″ N, 2°49′00″ W, and 54°44′09″ N, 2°48′36″ W, respectively). Both fields are mapped regionally as comprising the same broad soil type, namely the 711n Clifton Soil Association (Jarvis et al., 1984). This equates to the FAO Stagnosol soil group (WRB, 2015), which is a soil with Aquic properties within several USDA soil orders (USDA, 1999).

Field plots P1 (456 m^2) and P2 (232 m^2) are permanently grazed pasture and silage fields and receive heavy vehicular passes during silage cutting and slurry application. The land manager stated that neither has been plowed or aerated in recent years. Both sites have 4% slopes, although P1 is at the base of a slope and P2 is near a summit. Both fields belong to similar pastoral management systems and were continually grazed throughout the experiment, with P2 grazed by sheep (8 ha^{-1}) and dairy cattle (0.75 ha^{-1}), and P1 solely sheep grazed (15 ha^{-1}). As a result, the sampling sites were selected due to being mapped as the same soil type and having fairly similar management practices and are considered replicates within the study.

Table 1. A list of available studies that have investigated the effect of mechanical slit aeration on changes in overland-flow volumes.

Author	Study site	Soil type and texture	Rainfall mechanism	Rainfall depth	Rainfall intensity	Absolute overland flow change	Magnitude of overland flow change	Study notes
Shah et al. (2004)	West Virginia, USA	Ultic Hapludalf (silt loam)	Simulated (6 events)	28–65 mm per event	120 mm h^{-1}	−3 to +5 mm (aeration), −7 to +5 mm (aeration and aeration with liquid dairy manure)	−23 to +45% (aeration), −50 to +133% (aeration and aeration with liquid dairy manure)	Plot study
Franklin et al. (2006)	Georgia, USA	Aquic Hapludult (sandy-loam)	Simulated (2 events)	Not given	50 mm h^{-1}	−6.2 to +1.9 mm (aeration with broiler litter and inorganic fertilizer)	−32 to +10% (aeration with broiler litter and inorganic fertilizer)	Plot study
Van Vliet et al. (2006)	British Columbia, Canada	Aquic Dystroxerept (silt loam-sandy loam)	Natural (56 events)	1185 mm yr^{-1} avg. (4740 mm total)	Not given	−67.2 to −0.76 mm annually (aeration with liquid dairy and swine manure)	−81 to −47% (aeration with liquid dairy and swine manure)	Plot study: overland flow grouped from October–April over 4 yr
Franklin et al. (2007)	Georgia, USA	Typic Kanhapludults, Aquic Hapludults, Aquultic Hapludalfs (sandy loams)	Natural (133–203 events)	1037 mm yr^{-1} unaerated avg., 1051 mm yr^{-1} aerated avg.	Up to ∼100 mm per event.	Not given.	−35 to +3% (aeration)	Before and after paired watershed approach
Butler et al. (2008)	Georgia, USA	Typic Kanhapludult (sandy loam)	Simulated (2 events)	Not given	85 mm h^{-1}	Not given	−20 to +18% (aeration), −31% to +25% (aeration with broiler litter and slurry manure)	Plot study: before and after compaction overland flow experiments
de Koff et al. (2011)	Arkansas, USA	Typic Hapludults and Glossaquic Fragiudults (silt loams)	Simulated (11 events)	Not given	70 mm h^{-1}	−36.7 to −4.6 mm (aeration), −50.3 to +17.4 mm (aeration with poultry litter and swine slurry)	−74 to −8% (aeration), −75 to +16% (aeration with poultry litter and swine slurry)	Plot study

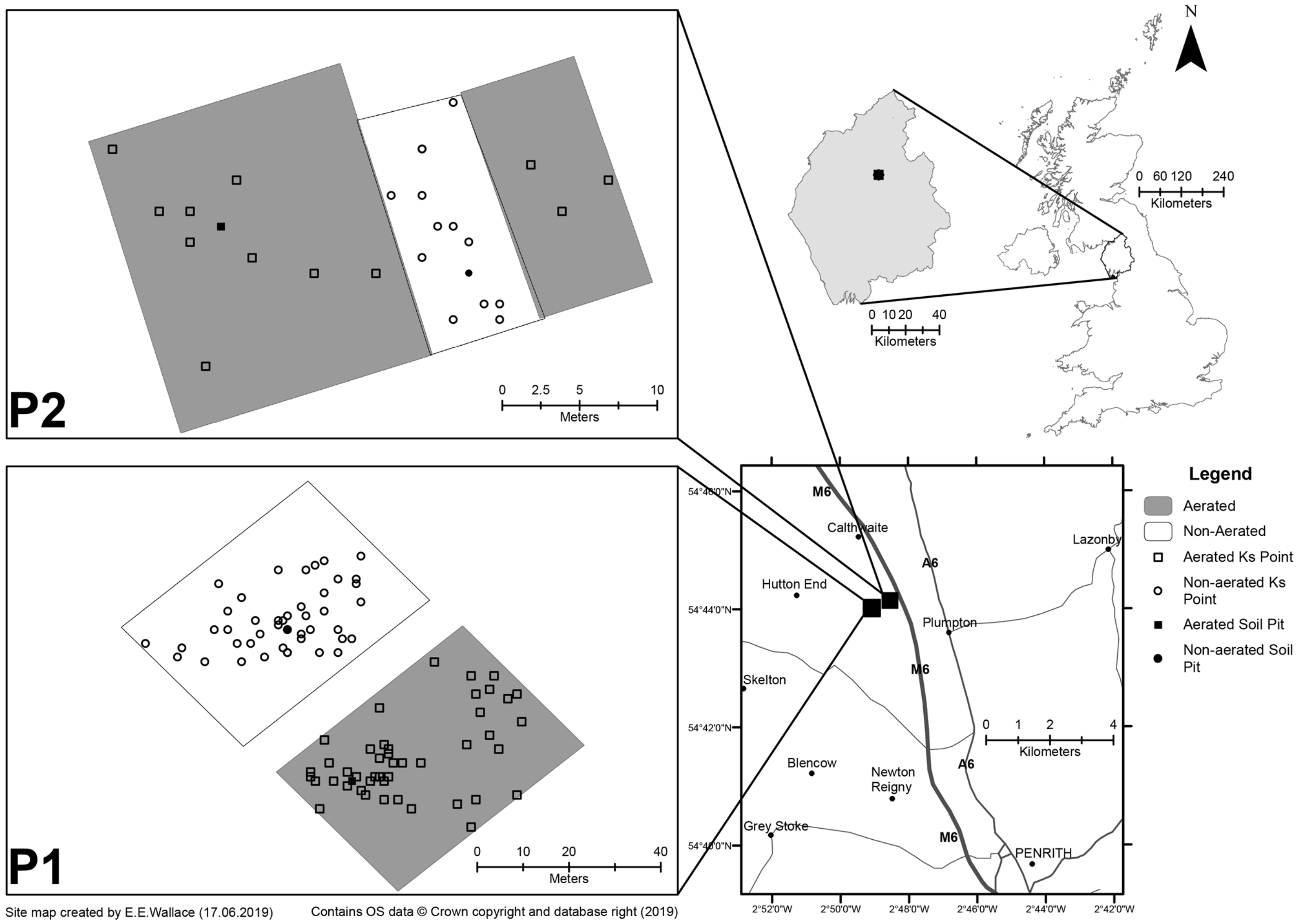

Fig. 1. Location of the experimental site within Cumbria, UK, together with the georeferenced locations of permeability (K_s) measurements within the aerated (gray shaded) and unaerated (white shaded) plots in both Field P1 and Field P2. Contains OS data Crown copyright and database right (2019).

During the final sampling experiment, 0.6-m-deep soil pits were manually excavated at random locations within aerated (P1A and P2A) and unaerated plots (P1N and P2N, Fig. 1), for the determination of reference soil properties. Soil was extracted using a 221-cm^3 bulk density cylindrical ring at 5-cm increments from the soil surface to 20 cm, totaling four soil samples per reference pit. Samples were oven dried at 105°C for 24 h for dry bulk density calculation. Organic matter (OM) content was determined from the bulk density cores via a 550°C 6-h loss-on-ignition test. Particle size analysis involved sieving oven-dried soil through a 2000-μm sieve, mixing the sample with 1% sodium polymetaphosphate for 24 h, followed by high-power sonication for 3 min and laser diffraction (Beckman Coulter, LS-13-320).

Aeration Treatment

The experiment began in June 2018 during an atypically dry summer (Supplemental Table S1). Each of the two replicates (P1 and P2) was randomly divided into two areas—one with blade aeration to a depth of 10 cm (denoted as subarea "A" in pasture names), and a control (unaerated, denoted as subarea "N" in pasture names). Aeration was applied on 11 June 2018, using a Ritchie 863G 3M (Ritchie Agricultural) blade aerator. The aerator operates two in-series rotor shafts, each with nine rotatable discs that individually have three blades angled 120° apart. Discs are spaced 23 cm apart within each rotor shaft, with a 17.5-cm gap between rotors. The 475-kg aerator was fully ballasted (with an additional 700 kg) during operation to increase blade ground penetration and traversed the replicates at an approximate rate of 1 ha h^{-1}. No markings or blade insertion paths were visible on the sward or soil surface 2 wk post-treatment.

Field Measurements

A total of 1368 penetration resistance and 114 permeability measurements were taken in the plots P1A, P1N, P2A, and P2N via random sampling throughout the experiment. Samples were taken 2, 6, 13, and 21 wk post-aeration (Supplemental Table S1, Supplemental Fig. S1).

Soil penetration resistance was measured using an SC900 Field Scout soil compaction meter using a 12.8-mm-diam. cone. The device measures PR via an internal load cell and has a maximum load capacity of 9000 kN. An ultrasonic depth sensor recorded measurement depths at 2.5-cm increments to a depth of 15 cm. The PR samples were taken randomly throughout each replicate, with efforts made to avoid disturbed soil or aeration slits. Measurements that exceeded meter capacity were also recorded.

Topsoil permeability was measured using a Talsma ring permeameter (see Talsma, 1960; Bonell et al., 1983; Chappell and Ternan, 1997). This constant-head technique gives measurements of the coefficient of permeability, also called the saturated hydraulic conductivity (K_s). Permeability was calculated via Darcy's law once steady state was achieved through the soil core. The procedures detailed in Chappell and Ternan (1997) were followed exactly except that the 10-cm-deep soil core was tested while inserted into the ground. This was done so that vertical water percolation out of any 10-cm-long slits within the core was into underlying soil (see Sherlock et al., 2000).

Statistical Analysis

The K_s frequency distributions are expected to be strongly positively skewed (Baker, 1978; Bonell et al., 1983; Zhai and Benson, 2006). Consequently, it was likely that a nonparametric statistical test was needed (i.e., Mann–Whitney-Wilcoxon [MWW]), and a parametric approach would only be adopted if results satisfied normality. The MWW tests were conducted within the MATLAB programming environment (Mathworks), using the ranksum function with significance levels of 0.05, 0.01, and 0.001.

Statistical comparisons of the permeability frequency distributions from each replicate were made with local rainfall intensities to estimate IEOF likelihood to create a peaks-over-thresholds statistical model. A 25.5-yr rainfall time series recorded at a 15-min resolution from the Skelton rain gauge (54°42′59″ N, 2°52′38″ W) was compared with the summary statistics (minimum, 10th percentile, lower quartile, median, and upper quartile) of K_s, to account for climatic variability within IEOF likelihoods. The rain gauge is 4.3 km southwest of P1 and 4.8 km southwest of P2. Both replicates are considered to have identical rainfall inputs given the prevailing frontal systems.

Results and Discussion

Reference Soil Properties

Soil pits were excavated in both fields for visible soil characterization and sampling to determine reference soil properties. At the P1A pit (Fig. 1), an O-horizon extended to 3 cm. An A-horizon existed between 3 and 12 cm but was weakly defined from the B-horizon. The B-horizon extended to 45 cm and contained redoximorphic features, before a well-defined sandy C-horizon. The P1N pit similarly had an O-horizon to 3 cm and an A-horizon from 3 to 10 cm. The B-horizon was visibly denser and stonier, extended to 40 to 45 cm, and contained redoximorphic features. The P2A and P2N pits had an O-horizon to 5 cm and an A-horizon between 5 and 10 to 12 cm. The B-horizon extended to 35 to 45 cm and was visibly heavier and stonier than the topsoil.

From the physiochemical analysis, the aerated plots in both replicates had substantially greater medium to very coarse sand contents (40–43%) in the upper subsoil (15–20 cm, Tables 2 and 3) compared with the unaerated plots (5–12%). Greater OM content at the 0- to 10-cm depth where roots are commonly found was observed in the aerated plots, with averages of 9.5 and 9.5% for P1A and P2A, and 8.4 and 7.0% for P1N and P2N, respectively. Overall, however, the unaerated plots in P1 and P2 had similar reference characteristics, as did aerated plots, although minor differences were apparent between adjacent pits within the same replicate.

Soil Penetration Resistance Differences between Aerated and Unaerated Plots (0–15 cm)

A total of 1368 PR tests were undertaken across all replicates. Some 46% of measurements were too dense (i.e., PR exceeded 7000 kPa) to give a reading (Table 4). The two replicates were very different in the numbers of tests that exceeded 7000 kPa. In P2, some 76% of tests on aerated topsoil and 75% on unaerated soil exceeded 7000 kPa during the first measurement date, whereas this was only 35% of aerated topsoil tests and 53% of unaerated topsoil tests in P1 (Table 4). This implies that P2 had more pockets of either (i) compacted topsoil or (ii) drier topsoil than P1.

As the experiment progressed, PR failures and measurable PR generally decreased as soils likely became increasingly saturated (Table 4, Supplemental Fig. S1; Cotching and Belbin 2007). Pasture P1A had noticeably fewer test failures and lower PR than P1N throughout the experiment, whereas PR values and test failures within P2 were almost identical between treatments.

Measurable PR highlights significant differences in P1 between treatments 2 wk post-aeration (Table 4), at 5 ($p \leq 0.001$), 7.5 ($p \leq 0.004$), and 10 cm ($p \leq 0.007$). The aerated site had a lower average penetration resistance (1876 vs. 2384 kN, 2283 vs. 2690 kN, and 2545 vs. 3060 kN) compared with P1N, for 5, 7.5, and 10 cm, respectively. The lower PR within P1A persisted with repeated monitoring, with significant differences at 5 to 15 cm in Week 6, 2.5 to 15 cm in Week 13, and 0 cm and 10 to 15 cm in Week 21. Contrastingly, within P2, P2A had either equivalent or slightly higher PR in comparison with P2N, with the aerated plot being significantly more compacted ($p \leq 0.014$) at the 10-cm depth.

Two alternative explanations are proposed to explain PR findings, although other interpretations are possible. The first explanation (Explanation 1) is that aeration caused PR improvements within P1 but was ineffective within P2. Slit aeration is believed to alleviate soil compaction through the soil-loosening effects of the rolling blades or tines (Davies et al., 1989; Douglas et al., 1995), so it may have lowered PR within P1. Slits may produce preferential infiltration (both rainfall and slurry; Crawford and Douglas, 1993; Douglas et al., 1995), which may preferentially wet soil around slits and reduce density within aerated plots (see Cotching and Belbin, 2007).

Table 2. Physiochemical properties of the two soil pits in Field Pasture 1 (P1).

Land use	Depth	Particle size distribution					Soil texture	pH	Organic matter	Bulk density
		≤2 μm	2–20 μm	20–60 μm	60–200 μm	200–2000 μm				
	cm	%							%	g cm^{-3}
P1 (aerated)	0–5	2.7	11.0	17.6	40.8	27.8	Sandy loam	5.87	11.4	1.01
P1 (aerated)	5–10	4.6	18.2	22.6	38.6	15.9	Sandy loam	5.82	7.7	1.15
P1 (aerated)	10–15	4.0	17.3	21.5	34.3	22.8	Sandy loam	5.97	7.7	1.04
P1 (aerated)	15–20	2.6	10.3	13.5	30.8	42.8	Sandy loam	6.12	7.0	1.32
P1 (unaerated)	0–5	4.3	17.9	17.9	27.8	32.1	Sandy loam	5.91	9.1	1.09
P1 (unaerated)	5–10	3.2	12.6	11.3	19.8	53.0	Sandy loam	5.96	7.1	1.11
P1 (unaerated)	10–15	11.3	41.6	23.7	22.0	1.3	Silt loam	6.12	4.7	1.87
P1 (unaerated)	15–20	8.5	34.2	25.3	27.4	4.6	Silt loam	5.67	4.8	1.33

Table 3. Physiochemical properties of the two soil pits in Field Pasture 2 (P2).

Land use	Depth	Particle size distribution					Soil texture	pH	Organic matter	Bulk density
		≤2 μm	2–20 μm	20–60 μm	60–200 μm	200–2000 μm				
	cm	%							%	g cm^{-3}
P2 (aerated)	0–5	2.7	11.7	15.6	40.1	29.8	Sandy loam	5.92	12.8	0.79
P2 (aerated)	5–10	4.6	20.4	24.5	38.7	11.8	Sandy loam	5.98	6.2	1.42
P2 (aerated)	10–15	6.6	29.0	29.2	31.7	3.5	Silt loam	6.23	4.2	1.09
P2 (aerated)	15–20	4.7	19.1	14.1	22.3	39.8	Sandy loam	6.73	4.3	1.67
P2 (unaerated)	0–5	5.7	24.1	20.7	24.0	25.5	Sandy loam	6.43	9.2	1.17
P2 (unaerated)	5–10	3.5	16.3	19.4	36.4	24.3	Sandy loam	6.83	4.8	1.18
P2 (unaerated)	10–15	4.1	17.3	21.3	35.5	21.8	Sandy loam	6.94	5.9	1.18
P2 (unaerated)	15–20	5.7	23.5	24.5	33.9	12.4	Sandy loam	6.94	3.3	1.52

Table 4. Soil penetration resistance statistics, including the percentage of successful measurements, median ($\tilde{x}$) and mean ($\bar{x}$) penetration resistance, and the Mann–Whitney–Wilcoxon (MWW) p values between treatments in Field Pasture 1 (P1) and Field Pasture 2 (P2). Note that the median values are compared in the Mann–Whitney-Wilcoxon tests.

Environment	Statistic	Treatment	n	Depth						
				0 cm	2.5 cm	5 cm	7.5 cm	10 cm	12.5 cm	15 cm
P1 Week 1	Successful measurements (%)	Aerated	110	65	65	65	65	65	51	35
		Unaerated	110	47	47	47	47	44	18	9
	$\tilde{x}$ (kN)	Aerated		225	1242	1932	2312	2605	2450	2881
		Unaerated		276	1622	2518	2726	3105	2967	2881
	$\bar{x}$ (kN)	Aerated		612	1290	1876	2283	2545	2573	2887
		Unaerated		662	1504	2384	2690	3060	3071	3215
	MWW (p)			0.818	0.195	0.001***	0.004**	0.007**	0.144	0.521
P1 Week 6	Successful measurements (%)	Aerated	143	74	74	74	74	73	66	52
		Unaerated	142	44	44	44	44	43	25	13
	$\tilde{x}$ (kN)	Aerated		552	1035	1087	1138	1346	1690	1828
		Unaerated		742	1138	1518	1828	2380	2674	2967
	$\bar{x}$ (kN)	Aerated		604	983	1101	1220	1475	1754	1925
		Unaerated		765	1111	1560	1934	2406	2817	3047
	MWW (p)			0.170	0.104	0.001***	0.001***	0.001***	0.001***	0.001***
P1 Week 13	Successful measurements (%)	Aerated	150	77	77	77	77	77	75	73
		Unaerated	130	67	67	67	67	66	49	44
	$\tilde{x}$ (kN)	Aerated		345	552	552	552	621	690	724
		Unaerated		207	656	724	897	1329	1622	1690
	$\bar{x}$ (kN)	Aerated		374	563	558	566	634	740	812
		Unaerated		366	676	751	941	1382	1689	1755
	MWW (p)			0.522	0.006**	0.001***	0.001***	0.001***	0.001***	0.001***
P1 Week 21	Successful measurements (%)	Aerated	103	94	94	94	94	94	91	83
		Unaerated	93	64	64	64	64	64	52	43
	$\tilde{x}$ (kN)	Aerated		207	380	448	483	552	621	724
		Unaerated		310	448	380	448	621	897	1070
	$\bar{x}$ (kN)	Aerated		242	389	437	474	575	713	792
		Unaerated		314	448	409	516	822	1039	1086
	MWW (p)			0.031*	0.105	0.232	0.750	0.003**	0.001***	0.001***
P2 Week 2	Successful measurements (%)	Aerated	192	24	24	24	24	22	14	2
		Unaerated	193	25	25	25	25	23	13	3
	$\tilde{x}$ (kN)	Aerated		69	310	2380	3140	3864	4106	3812
		Unaerated		121	880	2070	2933	3191	2932	3847
	$\bar{x}$ (kN)	Aerated		553	1021	2107	2871	3558	3782	3829
		Unaerated		515	965	2120	2693	2963	3021	3565
	MWW (p)			0.315	0.990	0.442	0.263	0.014*	0.067	0.914

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Aeration can additionally disrupt dense and established root mats (Bhogal et al., 2011); this encourages new root growth, which could potentially lower PR. The observed OM differences in the 0- to 10-cm soil layer between treatments may indicate that aeration increased root growth at both replicates (see above).

The soil loosening, preferential infiltration (particularly during dry conditions), and root mat disruption and root growth may combine to create a favorable earthworm environment, enhancing earthworm activity and reducing PR. Eggleton et al. (2009), in a UK study, showed strong declines in earthworms during dry periods, and relative increases during saturated conditions, showing earthworm abundance and resultant bioactivity is strongly linked to soil moisture. Furthermore, Capowiez et al. (2009) demonstrate that by adopting reduced-compaction agricultural practices, earthworm colonization can increase by an average of 20%.

These albeit untested hypotheses complement Douglas et al. (1995), who found blade aeration to reduce topsoil bulk density in Scotland. Alternative soil loosening devices are capable of reducing pasture density. These include subsoilers, which operate at 35 to 50 cm to remove deep compacted layers (Harrison et al., 1994), and sward lifters, which operate at 15 to 35 cm (Newell Price et al., 2015). Subsoilers and sward lifters target deeper compaction than blade aerators and are mostly used to relieve compaction from heavy machinery (Bhogal et al., 2011).

The limited PR difference within P2 could be due to ineffective aeration, soil recompaction, soil textural disparity, no established root mat, and/or a sparser or less mobile earthworm population. Crawford and Douglas (1993) demonstrate that progressively drier soil causes shallower and less effective aeration. It was not apparent during treatment that replicates had inherently different soil moisture contents, and consequentially soil moisture measurements were not undertaken. It is possible, however, that replicates were at different saturations, and future researchers are advised to record soil moisture during aeration. Pasture P2 may have been drier than P1 due to being toward the summit as opposed to the base of a slope, and more recent slurry wetting within P1 may have increased antecedent soil moisture. This could have reduced blade penetration within P2.

The higher PR baseline (P1N vs. P2N) and denser B-horizon within P2 may additionally reduce aerator penetration depth (see Davies et al., 1989; Douglas et al., 1995). The higher PR baseline within P2 could be caused by dairy cattle, which may compact the topsoil so it is resistant to aeration, and/or rapidly remove aeration improvements. Drewry et al. (2000a) found that dairy cattle significantly increased topsoil bulk density by one third when comparing 97 sheep farms with 87 dairy farms in New Zealand, and they also noted that dairy farms had significantly lower K_s at 0 to 5 and 10 to 15 cm. It is also possible that P2 improvements were not apparent because P2A was intrinsically more compact due to greater silt concentrations (see above).

Indirectly observed factors could also have prevented PR improvement in P2. Higher observed OM content within P2A (9.5%), as opposed to P2N (7%), suggests that although new root growth may be occurring (not directly measured in this study), this has not reduced PR. This is potentially due to the lack of a dense root mat preceding aeration, as shown by the low OM within P2N. The higher PR baseline within P2 could additionally inhibit earthworm motility and therefore their ability to reduce soil density and resultant PR (Capowiez et al., 2009, 2014). Results support studies such as Van Vliet et al. (2006), who found no improvements to bulk density following blade aeration.

The alternate explanation (Explanation 2) is that a combination of the sampling method and natural soil variation falsely indicated aeration to have reduced PR within P1, when in reality it was effective in neither. The sampling method could have caused lower PR readings within the aerated region of P1, as the penetrometer could have entered into the aeration slits. However, the lack of visible slits 2 wk post-aeration makes this an untested hypothesis. The suggested ineffective aeration within P2 would also explain why PR is highly comparable between treatments, as the aerator may have failed to generate slits within P2, and the penetrometer therefore may have had either no slits or very shallow slits to enter.

Natural soil variation may also have falsely indicated aeration to have been highly effective in P1. The denser, stone-rich layer within the B-horizon of P1N compared with P1A may have inferred aeration to reduce PR in P1, as fewer PR measurements within the aerated plot would fail due to stone contact (Davies et al., 1989). Uniform stone coverage throughout P2 suggests similar PR profiles as was observed. Textural analysis also reveals disparity at the 10- to 15-cm depth between treatments, which may have caused or contributed to the observed differences, at least for deeper measurements.

Topsoil Permeability Difference between Aerated and Unaerated Plots

A total of 114 permeability tests were undertaken across the replicates (Table 5). Two weeks post-aeration in P1 (Table 5), the aerated topsoil permeability was a factor of 3.4 times higher than unaerated topsoil. The difference was statistically significant at $p \leq 0.004$ (Table 6). These results contrasted with P2, where the aerated and unaerated plot had similar K_s values ($p \leq 0.894$).

Repeat measurements (at random locations within the plots) within P1 shows P1A to have a larger K_s in Week 6 by a factor of 3.9 ($p \leq 0.002$), in Week 13 by a factor of 5.7 ($p \leq 0.001$), and in Week 21 by a factor of 7.5 ($p \leq 0.024$). Repeated measurements within the same treatment in P1 showed statistically significant higher K_s between the first (Weeks 2 and 6) and latter two sampling dates (Weeks 13 and 21, Table 6).

The K_s values derived from the Talsma ring permeametry tests are conducted under a constant applied head and percolation rate through the analyzed core, only once equilibrium is achieved (i.e., core and below-core conditions are fully saturated). The temporal K_s variation in P1 may imply, therefore, that soil cracking had developed due to the prolonged dry period preceding treatment (see Supplemental Fig. S1); these cracks gradually closed with repeated soil wetting in the subsequent autumn (see Bouma and Dekker, 1978). Topsoil K_s is highly sensitive to crack structure (i.e., secondary porosity or macroporosity) and is known to change as Stagnosols and Gleysols dry or conversely rewet (Chappell and Lancaster, 2007). The marked K_s changes over a 21-wk period within P1N despite no artificial intervention indicate that before-and-after (before–after–control–impact [BACI]) measurements would have been unsuitable to detect intervention improvements. Results suggest that parallel measurements of unaerated against adjacent aerated plots (paired-plot design) are needed, alongside BACI measurements of aerated plots. Combining the paired-plot and BACI approach in this study would have been very beneficial to the interpretation of results and is therefore recommended for future research.

The two previously proposed explanations can explain why aeration may have increased permeability within P1 and not P2, although other interpretations are again possible.

Explanation 1 proposes that aeration was effective within P1, yet ineffective within P2. Aeration may have increased P1 permeability due to a combination of soil loosening, root mat disruption, and/or enhanced soil bioactivity. The soil loosening effect of the blades may contribute to altering soil macroporosity to increase K_s. In addition, the perforation of a root mat potentially enhances water percolation, especially if it is well established (Bhogal et al., 2011). The proposed improved earthworm environment (see above; Edwards and Lofty, 1977) may also have increased earthworm colonization within P1A and improved permeability (see Capowiez et al., 2009, 2014). Results support other published research suggesting that aeration may increase infiltration rates (de Koff et al., 2011) and reduce runoff (Van Vliet et al., 2006; de Koff et al., 2011). Similarly to PR, sward lifters (Drewry and Paton, 2000; Newell Price et al., 2015) and subsoilers (Harrison et al., 1994) are capable of increasing pasture K_s, although these operate at different depths to blade aeration.

The failure of aeration to increase permeability within P2 may be due to either ineffective aeration, soil re-compaction, no disruptable root mat, reduced earthworm abundance and activity (see above), or impermeable subsoil nullifying improvements. Impermeable subsoil could restrict K_s improvements within P2, as subsoil may nullify topsoil improvements if it is the limiting K_s factor. This questions the practical applications of ex situ permeability tests that are commonly adopted during related studies (e.g., Drewry and Paton, 2000; Drewry et al., 2000b), if done on sites with impermeable subsoil (see Chappell and Ternan, 1997; Sherlock et al., 2000). For aeration to reduce flood risk, it is likely necessary for infiltrated water to percolate vertically through the subsoil rather than follow rapid near-surface flows. Thus, aeration on slowly permeable topsoils that override permeable subsoils may produce the greatest flood-mitigation benefit.

Explanation 2 proposes that aeration was entirely ineffective, and natural soil variation falsely indicated aeration to improve K_s within P1. Stagnosols are typically slowly draining (Jarvis et al., 1984), so slight variation in macrostructure between P1 treatments could influence readings (see Bouma and Dekker,

Table 5. Saturated hydraulic conductivity summary statistics for Field Pasture 1 (P1) and Field Pasture 2 (P2).

Pasture	Sampling period	Min.	Q10†	Q25‡	Median	Q75§	Max.	Geometric mean	CV	*n*
		mm h^{-1}							%	
P1	Week 2 (aerated)	304.2	472.7	955.7	1872.8	2746.2	7356.1	1587.4	88.5	11
	Week 2 (unaerated)	143.1	155.0	214.8	459.8	754.0	2107.0	461.5	89.2	11
	Week 6 (aerated)	1331.6	1572.0	1742.4	2794.1	4300.4	7361.7	2885.0	55.4	12
	Week 6 (unaerated)	226.5	265.0	327.5	501.0	1678.0	4273.8	748.4	105.7	11
	Week 13 (aerated)	178.4	241.7	458.6	658.6	1188.2	2512.7	672.7	73.5	13
	Week 13 (unaerated)	10.4	37.8	54.4	170.8	331.2	427.2	118.3	82.1	13
	Week 21 (aerated)	16.8	60.6	206.6	316.0	779.1	886.4	300.8	71.4	9
	Week 21 (unaerated)	3.3	6.7	12.6	21.0	107.9	3633.3	40.0	269.9	9
P2	Week 2 (aerated)	40.5	75.8	132.2	306.8	588.8	1365.5	263.6	93.7	12
	Week 2 (unaerated)	132.0	138.7	172.9	321.6	520.9	928.7	311.4	62.7	13

† Q10, 10th percentile.

‡ Q25, 25th percentile.

§ Q75, 75th percentile.

Table 6. Saturated hydraulic conductivity Mann–Whitney–Wilcoxon (MWW) tests between aerated and unaerated treatments in Field Pasture 1 (P1) and Field Pasture 2 (P2).

Treatment	Mann–Whitney–Wilcoxon test (*p*)									
	Field Pasture 1								Field Pasture 2	
	Aerated treatment				Unaerated treatment				Aerated treatment	Unaerated treatment
	Week 2	Week 6	Week 13	Week 21	Week 2	Week 6	Week 13	Week 21	Week 2	Week 2
Week 2 (aerated)	–	0.091	0.013*	0.002**	0.004**				–	0.894
Week 6 (aerated)		–	0.001***	0.001***		0.002**				
Week 13 (aerated)			–	0.144			0.001***			
Week 21 (aerated)				–				0.024*		
Week 2 (unaerated)					–	0.365	0.006**	0.006**		–
Week 6 (unaerated)						–	0.001***	0.002**		
Week 13 (unaerated)							–	0.083		
Week 21 (unaerated)								–		

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

1978). However, soil data from P1 (given above) suggest only minor textural difference. Furthermore, P1 plot boundaries are only 10 m apart, with plot centers only 50 m apart (Fig. 1). Thus, the supporting soil data and plot proximity dispute this, but it remains possible. Explanation 2 supports several related studies that found aerators to negligibly reduce runoff (Franklin et al., 2006; Butler et al., 2008). The proposed BACI-paired-plot approach for K_s measurements would test this hypothesis and is therefore recommended for future research.

Permeability Comparison with Local Rainfall Intensity

A recent 25.5-yr record (1990–2018, excluding July 1993–March 1997) for the Skelton rain gauge, comprising of 847,320 values sampled at 15-min intervals, shows that rain occurred during 66,985 of those intervals (7.91% of the time). The maximum observed rainfall intensity (MORI) for this period was 21.2 mm 15 min^{-1}. Converting the K_s data into millimeters per 15 min and overlaying this with rainfall generates IEOF likelihood (where rainfall intensities exceed the topsoil K_s; Supplemental Tables S2 and S3; Horton, 1933).

During Week 2 in P1 (Supplemental Table S2), the minimum observed K_s for both aerated (76 mm 15 min^{-1}) and unaerated (35.8 mm 15 min^{-1}) plots, exceeds the MORI. This suggests little to no potential for IEOF generation at P1 in either treatment. For Week 2 in P2 (Supplemental Table S3), six intervals (0.00896% of rainfall periods) surpass the K_s minimum in the aerated site (10 mm 15 min^{-1}), and one interval (0.00149% of rainfall periods) surpasses the 10th percentile of the aerated site (19 mm 15 min^{-1}), whereas the minimum K_s within the unaerated region (33 mm 15 min^{-1}) exceeds the MORI. This suggests aeration to potentially cause very minor increases in IEOF likelihood within P2.

Repeat sampling at P1 (Supplemental Table S2) in Week 6 highlights that virtually no IEOF would likely be generated for both treatments, with an aerated minimum K_s of 333 mm 15 min^{-1}, and an unaerated minimum K_s of 56.8 mm 15 min^{-1}. Week 13 in P1 demonstrates the aerated minimum K_s (44.5 mm 15 min^{-1}) to exceed the MORI, yet 234 intervals (0.349% of rainfall periods) exceed the unaerated minimum K_s (2.5 mm 15 min^{-1}), six (0.00896% of rainfall periods) exceed the 10th percentile (9.5 mm 15 min^{-1}), and three (0.00448% of rainfall periods) exceed the lower quartile (13.5 mm 15 min^{-1}). This highlights aeration's potential to substantially reduce IEOF likelihood 13 wk post-treatment. During Week 21, in P1, rainfall intensities exceed some K_s threshold in both treatments, with aeration causing substantial reductions in IEOF likelihood at the minimum (7546 fewer intervals, 11.3% of rainfall periods), 10th percentile (726 fewer intervals, 1.08% of rainfall periods), lower quartile (107 fewer intervals, 0.160% of rainfall periods), and median (40 fewer intervals, 0.0597% of rainfall periods).

Without direct OF measurements or resulting streamflow, it is not possible to state if IEOF likelihood changes can make a noticeable difference at whole-field or stream microcatchment scales. This is because IEOF generated on micropatches of topsoil may infiltrate as it traverses adjacent micropatches of more permeable soil, so called "runoff–runon phenomena" (Bonell and Williams, 1986). Assuming Explanation 1 to be true, Weeks 13 and 21 at P1 imply that aeration may reduce flood risk (at least on a subfield scale), as $\geq$25 and $\geq$50%, respectively, of the P1N plot area could be generating IEOF for a considerable number of events (for 107 and 40 15-min intervals, respectively). In contrast, only three 15-min intervals had the potential to generate IEOF on $\geq$10% of the P1A plot area, and no recorded rainfall intensity had the potential to generate IEOF on $\geq$25% of P1A. The very minor likelihood of increase in IEOF due to aeration in P2 is unlikely to cause a noticeable difference in flood risk, as it affected $\geq$25% of P2A for only a single 15-min period, and $\geq$10% of P2A for only six 15-min periods. This deduction implies that blade aeration may have the potential to reduce flood risk in regions where topsoil permeability conditions mean that IEOF is a frequent flood-generating mechanism. Pasture P1 findings support Van Vliet et al. (2006) and De Koff et al. (2011), who found aeration to reduce OF. Pasture P2 results support the negligible changes observed in Shah et al. (2004), Franklin et al. (2006), and Butler et al. (2008).

Summary and Conclusions

Overland flow potentially amplifies flood risk across various regions of the world, yet previous research investigating if aeration reduces OF has revealed mixed findings. To improve process interpretation, two highly similar UK Stagnosol pastures (P1 and P2) underwent blade aeration and subsequent topsoil penetration resistance and permeability measurements over 21 wk. Permeability and precipitation information gathered from each replicate was used to generate IEOF likelihood, to assess if blade aeration could reduce this fast drainage pathway.

Blade aeration significantly reduced PR for at least 21 wk post-aeration in P1, although P2 showed no significant changes to penetration resistance, with a significant increase at 10 cm. The permeability results highlight that aeration significantly improved topsoil permeability for at least 21 wk post-treatment in P1, although no permeability improvement was observed within P2. Proposed reasons for increases in permeability and decreases in PR are blade-induced soil loosening, preferential infiltration, root mat disruption, and/or increased soil bioactivity. The P1 peaks-over-thresholds analysis highlights that aeration can substantially reduce IEOF likelihood from up to 11.4% of rainfall periods pre-aeration to 0.0926% of rainfall periods post-aeration, although aeration within P2 caused no change in IEOF likelihood. Results highlight that aeration has the potential to reduce flood risk in areas with elevated IEOF likelihood, although improvements can be site specific.

Future aeration researchers are advised to include root density and earthworm diversity for improved system interpretation. Researchers should additionally include soil moisture measurements and blade penetration depth during aeration to validate aerator effectiveness. X-Ray tomography after aeration would also determine the effects of aeration on soil macroporosity. Future studies are advised that if blade insertion points and paths cannot be determined (either visually or via georeferencing), soil penetrometers may enter slits and bias measurements of penetration resistance. Similarly, studies are invited to question the suitability of ex situ permeametry for their study sites. Finally, future research should consider combining the paired-plot and BACI approaches, to rule out natural soil variation causing observed differences.

Supplemental Material

The supplemental material consists of the treatment and sampling timetable for both pastures (Supplemental Table S1). A daily rainfall time series taken from Skelton is provided to infer site conditions prior to treatment, as well as during and between sampling dates (Supplemental Fig. S1). The statistical peaks-over-thresholds model is shown for Pasture 1 (Supplemental Table S2) and Pasture 2 (Supplemental Table S3). The peaks-over-thresholds statistical model highlights the number of precipitation events that surpass each K_s summary statistic (minimum, 10th percentile, lower quartile, median, and upper quartile), and therefore the implied reduction in IEOF events.

Conflict of Interest

The authors declare no conflict of interest.

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