Phosphorus and nitrogen losses from temperate permanent grassland on clay-loam soil after the installation of artificial mole and gravel mole drainage

N. Valbuena-Parralejo, O. Fenton, P. Tuohy, M. Williams, G.J. Lanigan, J. Humphreys

PII: S0048-9697(18)35018-6
DOI: https://doi.org/10.1016/j.scitotenv.2018.12.173
Reference: STOTEN 30007

To appear in: *Science of the Total Environment*

Received date: 30 August 2018
Revised date: 10 December 2018
Accepted date: 11 December 2018

Please cite this article as: N. Valbuena-Parralejo, O. Fenton, P. Tuohy, M. Williams, G.J. Lanigan, J. Humphreys , Phosphorus and nitrogen losses from temperate permanent grassland on clay-loam soil after the installation of artificial mole and gravel mole drainage. Stoten (2018), https://doi.org/10.1016/j.scitotenv.2018.12.173

Phosphorus and nitrogen losses from temperate permanent grassland on clay-loam soil after the installation of artificial mole and gravel mole drainage

N. Valbuena-Parralejo*[a, b], O. Fenton[c], P. Tuohy[a], M.Williams[b], G.J. Lanigan[c] and J. Humphreys[a]

[a]*Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland*

[b]*TCD School of Natural Sciences, Botany Department, Trinity College Dublin, Collage Green, Dublin 2, Ireland*

[c]*Environment Research Centre, Teagasc, Johnstown Castle, Wexford, Co. Wexford, Ireland*

* Corresponding author. Tel: +353 25 42505; E-mail: valbuenn@tcd.ie

Abstract

Mole (M) and gravel-mole (GM) drainage systems improve the permeability of soils with high clay contents. They collect and carry away infiltrating water during episodic rainfall events. Characterisation of nutrient fluxes (concentration and flows) in overland flow (OF) and in mole drain flow (MF) across sequential rainfall events is important for environmental assessment of such drainage systems. The objective of this study is to assess the impact of drainage systems on soil nutrient losses. Three treatments were imposed on grazed permanent grassland on a clay loam soil in Ireland (52°30’N, 08°12’W) slope 1.48%: undrained control (C), mole drainage (M) and gravel mole drainage (GM). Plots (100 m x 15 m) were arranged in a randomised complete block design with four replicated blocks. Nitrogen (N) and phosphorus (P) concentrations in OF, MF and groundwater (GW) were measured from each plot over 15 consecutive rainfall events. The results showed that M and GM (P<0.05) deepened the watertable depth and decreased OF. M and GM increased losses of nitrate-N (22%) and ammonium-N (14%) in GW. Nitrate-N concentrations from all the flow pathways (mean and standard error (s.e.): 0.99 s.e. 0.10 mg L-1) were well below the 11.3 mg L-1 threshold for drinking water. Ammonium-N concentrations from all the flow pathways (mean: 0.64 s.e. 0.14 mg L-1) exceeded drinking water quality standards. On the other hand M and GM lowered total P losses (mean annual losses from C, M and GM: 918, 755 and 853 s.e. 14.1 g ha-1 year-1) by enhancing soil P sorption. Hence M and GM can be implemented on farms under similar management to that described in the present study with a minor impact on N (increased concentration on averaged 18% to GW) and P (reduced by on avenged 114 g ha-1 year-1).

Keywords: Mole and gravel mole drainage, phosphorus, nitrate, ammonium, pathways interactions.

1. Introduction

Mole drainage (M) is widely used internationally as a shallow drainage technique in soils exhibiting low permeability in upper horizons (Burke et al., 1974; Haygarth et al., 1998; Ibrahim et al., 2013; Sharpley and Syers, 1979; Tuohy et al., 2015). Mole drainage can improve the permeability of upper soil horizons and can thereby increase the rate of water discharged through the soil profile (Tuohy et al., 2015). In Ireland, many dairy farms are located in high rainfall areas, dominated by poorly-permeable soils and low evapotranspiration rates, which results in poor trafficability by livestock and machinery after rainfall events, especially in spring and autumn (Fitzgerald et al., 2008; Keane, 1992; Tuohy et al., 2016). Achieving a long grazing season on permanent grassland is key to profitable ruminant livestock production in many temperate grassland regions (Dillon et al., 2005; Shalloo, 2009). Therefore, mole and gravel mole drainage (GM) are land management techniques that improve trafficability and, ultimately, profitability on farms.

Although phosphorus (P) and nitrogen (N) are present in the soil, nutrient losses in overland flow and flow emanating from mole drains highly depend on soil permeability (McDowell et al., 2001, Ibrahim et al., 2013). Moreover, areas with high soil nutrient contents along with high volumes of runoff and drainage are recognized as being of high risk of nutrient loss to water (Haygarth et al., 1998; Peukert et al., 2014; White et al., 2009). Previous research has shown that installation of M or GM drains can change the volume of flows between overland flow and mole flow (Tuohy et al., 2016; Tuohy et al., 2015). Hence to fully assess the impact of installation of mole or gravel mole drains there is a need to make an integrated assessment of N and

P losses encompassing the various loss pathways including overland flow, mole flow and loss to groundwater.

The objective of this experiment was to quantify the effects of mole and gravel mole drainage systems on losses of P and N in (i) overland flow, (ii) mole flow and (iii) ground water flow under a grass-clover based dairy production system over 15 episodic rainfall events during one year. Phosphorus and N species were investigated in terms of mean concentration (mg L^{-1}) and mean fluxes (g $ha^{-1}h^{-1}$) from the following treatments: un-drained control (C); mole drainage (M) and gravel mole drainage (GM).

2. Materials and methods

2.1 Experimental layout and design

This experiment was conducted at Solohead Research Farm (52°30'N, 08°12'W), on a gently sloping (1.4%) site (2.5 ha) bounded by the river Pope. The average annual rainfall from the preceding 10 years (2004 to 2013) was 1017 mm with annual potential evapotranspiration of approximately 510 mm. During the study period, 31 March 2014 until 30 March 2015, total annual effective drainage was 565 mm, occurring on 260 days and the 73% between November and March. The soils were poorly drained Gleys with a clay loam texture; Subsoil was quaternary till with a shallow watertable (0 to 2.2 m below ground level) (Tuohy et al., 2016). The soil type was grouped under the Elton soil association (Creamer et al., 2014). Soil physical and chemical properties are presented in Table 1.

Prior to 1996 there were high nutrient inputs to this site applied as dairy manure. Although these applications ceased in 1996 and there were no subsequent applications of P and K fertilizers, there remained a legacy of high soil P and potassium concentrations at this site (0 to 10 cm depth). Following extraction using Morgan's solution (Na acetate + acetic acid, pH 4.8), mean soil Morgan's P concentrations was 27.4 (s.e. 1.12) mg L^{-1} and mean soil Morgan's potassium concentrations was 184 (s.e. 24) mg L^{-1}. To put these concentrations in context, no agronomic response is expected to soil Morgan's P >8.0 mg L^{-1} and soil Morgan's potassium >150 mg L^{-1} (Coulter et al., 2008).

The experimental site, layout and design has been described previously by Tuohy et al. (2016) and Valbuena-Parralejo et al. 2019. Three of the four treatments described on previous studies were used in the present study. They were an un-drained control (C), mole drainage (M) and gravel mole drainage (GM). In August 2010 a large open V-shaped drain (2 m depth and 4 m wide at ground level) was excavated along a natural depression in the site running along a west-east axis with water exiting into the river Pope from the eastern end of the open drain (Figure 1). All the runoff and drainage flow discharged to the open drain and then to the river Pope. The experimental site was hydrologically isolated from external lateral water movement by an isolation ditch, comprising a 1 m deep trench filled to the soil surface with stone aggregate (Figure 1). In January 2011 the site was divided into four blocks (each 60 m-wide, 100 m-long). Each block was sub-divided into four 15 m wide plots. To avoid lateral surface flow between adjacent plots, each plot was flanked by berms consisting of a 0.2 m deep trench and 0.30 m high embankment of compacted soil. Treatments were assigned to plots in a randomized complete block design with four replications.

Treatments were imposed in July 2011. Treatment M was installed using a simple mole plough at a depth of 0.55 m. This installation depth ensured that the mole channels were located in a heavy, plastic, poorly permeable and stone-free layer of the soil. All the latter soil properties were required in order to succeed on the mole channel formation and stabilisation. The distance between each mole channel, laid parallel to each other, was 1.2 m.

Treatment GM was installed using a gravel mole plough. It consisted on the same principle as the simple mole plough but back-filled with gravel. The GM was installed at a depth of 0.40 m, which was the maximum attainable by the implement used. The distance between each channel was 1.2 m. The gravel mole plough was set to install a 0.20 m high column of clean gravel aggregate (10 to 20 mm diameter) along the formed channel (Figure 2).

Treatment M consisted of unlined channels formed in subsoil by pulling a cylindrical torpedo-shaped foot through the subsoil. The torpedo-shaped foot was attached to a blade-shaped leg that was connected to the three-point linkage of the tractor. A plug (or expander) was attached to the end of the foot, which helped to compact the channel wall. Treatment GM was based on the same principal except that the channel created in the soil was immediately back-filled with gravel flowing from a hopper on top of the mole-plough down into and out through the leg and foot of the mole-plough.

Both M and GM treatments were installed to the full length of the plots (100 m). Further details are available in Tuohy et al. (2016). There were 11 mole or gravel mole channels installed in each of the drained plots. In order to avoid border effects, measurements were conducted on flows from the outlets of the five central mole channels in each drained plot (see below).

Two sub-plots (2 × 11 m) for watertable depth measurements were established along the long axis of each plot. One sub-plot was established in the upper half (up slope) and the second in the lower half (down slope) of the plots. Two piezometer, for water table depth measurements, were installed in each sub-plot. Details of the piezometers are provided below.

2.2 Measurements

2.2.1 Meteorological data

An automated weather-station (Campbell Scientific Ltd. Loughborough, UK) recorded rainfall, air temperature, soil temperature, wind speed, wind direction and solar radiation (resolution 30 min). The hybrid grassland model of Schulte et al. (2005), assuming poorly drained soil criterion, was used for estimation of the soil moisture deficit and effective drainage, there were calculated as the difference between precipitation and estimated evapotranspiration. The soil moisture deficit of a certain day was calculated in the model as soil moisture deficit of the previous day (both in mm) minus the actual rain plus the evapotranspiration (mm/day) and plus the amount of water drained (mm/day). The evapotranspiration was expressed as a function of the potential or reference crop evapotranspiration and the current soil moisture deficit. Equations are described by Schulte et al. (2005) and all values are estimated for the root zone, hence the first 15 cm of soil depth.

2.2.2 Water table depth

Two fully screened piezometers (HDPE pipes, internal diameter 19.6 cm - Eijkelkamp, Agrisearch Equipment, Giesbeek, The Netherlands) were installed in each sub-plot. The piezometers were installed 3 m below ground level using a soil pneumatic drill. Near the soil surface, the area between the soil and the pipe (0.03 m) was filled with bentonite to prevent water channelling down the outside the piezometer. The water table depth readings was measured from all the piezometers on weekly basis using an electronic dipper (Marton Geotechnical Services Ltd, Suffolk, U.K.).

2.2.3 Plant biomass production and N uptake

The grass-clover swards were rotationally grazed by lactating dairy cows at approximately monthly intervals during the main grazing season (March to November). The grazing rotation length varied from 21 days in late spring/early summer to 42 days in autumn. Cows were allowed to graze the swards when the sward height, measured using a Filips rising plate meter (www.grasstec.ie), reached 10 cm above ground level. Cows were removed from the plots when the sward height was 4 cm above the ground level. The swards received no inorganic fertiliser input; white clover (*Trifolium repens*) in the pasture was the main source of plant-available N via biologically fixed N.

Herbage production was measured from an area of 10 × 1.2 m within each plot. The herbage was harvested (Etesia UK Ltd, Warick, UK) and weighed before each grazing. A sub-sample of 100 g was dried for 16 h at 100 °C to determine the herbage matter content. A second 100 g sub-sample was stored at -20 °C before being freeze dried, milled to pass a 0.2 mm sieve and analysed for total N using a LECO 528 auto-analyser (LECO Corporation, St. Joseph, MI, USA). Uptake of N in herbage was calculated by multiplying herbage dry matter yield by the N concentration in harvested herbage for each sampling date; annual N uptake was calculated by summing values over one year.

2.2.4 Soil fertility

Plant-available P and potassium concentrations were determined for each plot before the experiment started. Fifteen soil samples were taken to 10 cm depth for each plot and extracted in Morgan's solution (1:5 (v/v) soil:solution ratio with a 10% sodium acetate solution buffered at pH 4.8).

2.2.5 Flow event delineation and antecedent conditions

A period of 12 hours without rainfall was used to separate one rainfall event from another, similar to other studies (Ibrahim et al., 2013; Kurz et al., 2005; Tuohy et al., 2015). The mole and gravel mole drains were only transmitting water during and shortly after rainfall events. Therefore the start and the end of each flow event was clearly defined as the periods when water was not flowing from the mole drains outside the timeframe of rainfall events.

A total of 15 rainfall events were captured and analysed in this study (31 March 2014 until 31 March 2015) (Table 2).

2.2.6 Overland and mole drain flows

The overland flow from each plot was collected through the lateral berms and channelled towards the lower end of each plot. The berms were piped towards a specific overland flow measurement tank for each plot. Likewise mole flow from the five central channels was piped to a specific mole flow measurement tank for each plot with Mole and Gravel Mole drainage channels. Each measurement tank (1.0 x 0.6

x 0.6 m, Carbery Plastics, Clonakilty, Co. Cork, Ireland) contained a v-notch weir through which overland flow or mole flow flowed towards the monitoring tank. To monitor flow rates each tank was fitted with a Sigma area/velocity probe connected to a Sigma 920 flowmeter (HACH Company, Maryland, USA). Flow rate from each tank was measured continuously with a resolution of 15 min. Mole flow results were adjusted to total plot area taking into account for the mole flow from five of the eleven Mole and Gravel Mole channels.

The ground water recharge was calculated based on the estimated effective drainage (Schulte et al. 2005) and the measured overland flow and mole flow. Ground water flow (mm) was calculated as: effective drainage – [overland flow + mole flow] = ground water flow.

2.2.7 Water sampling and analysis

Volumes of the overland flow and mole flow were measured in this study. Water samples associated with the measured volume were taken within a timeframe, approximately 180 min once rainfall started. There were a total of four overland flow measurement tanks for treatment control and four overland flow and four mole flow for treatments Mole and Gravel Mole, respectively. At every sampling occasion, throughout the rainfall event, a water sample of each flow pathway (overland flow and mole flow) was taken from each measurement tank. Hence a total of 60 samples were taken at each rainfall event (36 from overland flow and 24 from mole flow). Approximately 100 ml of water was taken from each flowing pipe using a sampling tube (Polylab Centrifuge Tube Conical Bottom, 50 ml. Sigma Aldrich, Co Wicklow, Ireland). Sampling was conducted 15 times between 8 May 2014 and 13 March 2015 (Table 2), which represented the total overland flow during this year.

In each plot one piezometer located in the up-slope was used to determine nutrient concentrations in ground water flow. Water samples were taken weekly, after purging the piezometers, during the rainfall event. At each sampling occasion each of the piezometers were emptied in the morning; all of the water standing in each well was pumped out using a manual hand pump and discarded. During the following 2 h the piezometers were allowed to recharge; water seeped back into the piezometer from the surrounding soil and through the piezometer screen. This ‘recharged’ water in each well was sampled. Approximately 100 ml of water was taken from each well using a large syringe.

From all the flow pathways (overland flow, mole flow and ground water flow) two 50 ml samples (A and B) were taken on each sampling occasion. Sample A was filtered using Whatman miliprore filter paper, d=132 mm, 0.45µm, and sample B remained unfiltered. All samples were analysed for total phosphorus (TP), dissolved reactive P (DRP), ammonium-N and nitrate-N using a Thermo Konelab 20 analyser (Technical Lab Services, Ontario, Canada).

By combining the results of the analyses of the filtered (A) and unfiltered (B) samples the results for the following P species were determined using the methodology described by Ibrahim et al. (2013); i.e. TP is the sum of the dissolved (TDP) and particulate P (PP), and TDP is the sum of DRP and dissolved unreactive P (DUP). Hence, the DUP was calculated from by TDP – DRP. The key results presented in this study are DRP, DUP and PP.

Nitrogen and P losses (kg ha^{-1}) for each treatment were estimated by multiplying the mean N and P concentrations (mg L^{-1}) recorded on the sampling date with the volume of overland flow or mole flow (mm) between two sampling occasions. For the ground water flow pathway DRP (kg ha^{-1}) were estimated by multiplying the mean DRP concentrations (mg L^{-1}) recorded on the sampling date with the volume of ground water flow (mm) between two sampling occasions. Likewise losses of all N species (kg ha^{-1}) were estimated by multiplying the mean N concentrations (mg L^{-1}) recorded on the sampling date with the volume of ground water flow (mm) between two sampling occasions.

2.2.8 Annual nutrient losses to water

The 15 rainfall events encompassed in this study accounted for 0.56 of the annual rainfall during the study period. The extent of annual losses was extrapolated from the 15 events to allow us to compare the results of the present study with other previous studies, where losses were quantified on an annual basis.

2.2.9 Statistical Analysis

The watertable depth, concentrations and fluxes (concentration × flow) (TP, PP, TDP, DRP, DUP, nitrate-N and ammonium-N) data were subjected to ANOVA using SAS 9.3 (SAS 2011, Institute Inc., Cary, NC, USA). Data below the limits of detection was considered following the methods described by Helsel 1990 to estimate the summary statistics. All data were checked for normality by using residual normality and variance analysis. All data required a natural logarithmic transformation [y = log (x)]. Some of the P and N species data required a different logarithmic transformation [y =

log (x+0.01)]. The value of 0.01 was added before log transforming the data, which was sufficient to prevent the generation of zero transformed values. The variables included in the model were treatment, sampling date and treatment by sampling date interaction. Sampling date was included as a repeated measure in the ANOVA. Extrapolated annual losses (g ha^{-1} $year^{-1}$) of TP, PP, TDP, DRP, DUP, nitrate-N and ammonium-N, N uptake in herbage, soil P and K concentrations were also subjected to ANOVA. All data were checked for normality by using residual normality and variance analysis. The variables included in the model were treatment and replicate. For both ANOVA models a Tukey-Kramer method test (Jaccard, J. et al., 1984) was carried out to determine differences between treatments. A statistical probability of $P < 0.05$ was considered significant for all statistical tests.

3 Results

3.1 Meteorological data

Annual rainfall during the study period was 1013 mm. Daily precipitation, effective drainage and soil moisture deficit data for the year beginning 31 March 2014 are presented in Figure 3; the timing of rainfall events is also indicated.

A total of 15 rainfall events were captured (Table 2). Of those, one event had less than 5 mm of rainfall, four had between 5 and 10 mm and rainfall during each of the other ten events was greater than 10 mm. Effective drainage during each of the 15 events ranged from 0.7 to 45.6 mm. Total event precipitation was the greatest for Event 10 (45.8 mm) and the least for Event 2 (4.2 mm).

3.2 Water table depth

The water table depth was consistently shallower ($P<0.05$) in C than in the drainage treatments. Mean pre-event water table depth was 1.2 m below ground in C compared with 1.3 and 1.5 m below ground for Mole and Gravel Mole, respectively, (standard error of the mean (SEM) 0.021); Post-event below ground means of 0.67, 0.90 and 1.06 m were recorded for Control, Mole and Gravel Mole, respectively, ($P<0.05$, SEM 0.033).

3.3 Soil fertility

There was no difference in soil Morgan's potassium concentrations between treatments. Mean soil Morgan's potassium was 184 (s.e. 24) mg L^{-1}, which was in excess of an agronomic response to applications of fertilizer ptassium (100 to 150 mg L^{-1}). Similarly, there was no difference in soil Morgan's P concentrations between treatments. Mean soil Morgan's P concentrations was 27.4 (s.e. 1.12) mg L^{-1}, which was very high, being well in excess of an agronomic response to applications of fertilizer P (5 to 8 mg L^{-1}) and classified as being at risk of environmental losses in overland flow (Coulter et al., 2008). Furthermore, there was no difference in annual N uptake in herbage between treatments. Mean annual N uptake in herbage across treatments was 459 (s.e. 6) kg ha^{-1}.

3.4 Volumes of Flow from the flow pathways

There was a greater overland flow from Control than from the Mole and Gravel Mole, which were not different from each other (Table 3). Mole drain flow was greater from Gravel Mole than Mole. There was no difference in flow being discharged to ground water flow between treatments. Overland flow accounted for 0.6 of the total flow from Control, which was a greater proportion than for the drainage treatments i.e. 0.36 and 0.37 from Gravel Mole and Mole, respectively (Table 3).

3.5 Concentrations of P

There were no differences in TP, DRP and DUP concentrations in overland flow between treatments (Table 4). The mean concentration of PP in overland flow was lower in Mole than Control and Gravel Mole, which were not different from each other.

In mole flow there were no differences in TP and DUP concentrations between Mole and Gravel Mole (Table 4). The mean concentration of DRP in mole flow was higher ($P<0.001$) from Gravel Mole than Mole. In contrast, PP concentration in mole flow was higher ($P<0.001$) in Mole than Gravel Mole.

There was no difference in DRP concentrations in ground water flow between treatments (Table 4).

3.6 Concentrations of N

There were no ($P<0.05$) differences in nitrate-N and ammonium-N concentrations in overland flow and in ground water flow between treatments (Table 4). Likewise there was no difference in ammonium-N concentrations in mole flow between treatments. In contrast, nitrate-N concentrations in mole flow were higher in Gravel Mole than in Mole.

3.7 Fluxes of P

The fluxes of TP ($P<0.05$) and DRP ($P<0.01$) in overland flow were higher from Control than from the drainage treatments, which were not different from each other (Table 5). There was no difference in the flux of DUP in OF between treatments. The flux of PP in overland flow from Control was greater ($P<0.05$) than that from Gravel Mole, which in turn was greater ($P<0.05$) than that from Mole (Table 5).

There was no difference ($P>0.05$) in the flux of TP and DUP in mole flow between the drainage treatments (Table 5). DRP losses in mole flow from Gravel Mole were greater ($P<0.001$) than from Mole. PP losses in mole flow were greater ($P<0.05$) from Mole than Gravel Mole.

3.8 Fluxes of N

The losses of ammonium-N and nitrate-N in overland flow were lower ($P<0.05$) from Mole than from the other two treatments, which were not different from each other (Table 5).

In the mole flow there was no difference in ammonium N between the drainage treatments (Table 5). Nitrate-N losses in mole flow were greater ($P<0.001$) from Gravel Mole than Mole.

There were no differences in losses of ammonium-N and nitrate-N to ground water flow between treatments (Table 5).

3.9 Annual losses

Statistical analysis showed that the captured rainfall events were representative of annual rainfall events during this study. The mean volume of rainfall for the annual rainfall events was 10 (s.e. 1.1) mm and the mean for the captured events was 15 (s.e.

2.8) mm. The captured rainfall events accounted for the 0.56 of annual rainfall. Hence annual losses were estimated based on the above.

The annual losses of TP ($P<0.001$) and DRP ($P<0.01$) across all the pathways (overland flow, mole flow and ground water flow) were the highest from Control, followed by Gravel Mole and Mole (Table 6). There was no difference in the annual losses of DUP and PP between treatments.

The annual losses of nitrate-N across all the pathways were lower ($P<0.001$) from Control than from the other two drainage treatments, which were not different from each other (Table 6). The annual ammonium-N losses across all the pathways were greater ($P<0.001$) from Gravel Mole than Mole, which was greater ($P<0.001$) than C (Table 6).

4. Discussion

During this study losses of P and N were measured during 15 rainfall events and we also calculated annual losses in order to compare the results of the current study with previous studies that measured annual losses from the agri-ecosystem.

4.1 Phosphorus loss to water

This site had a legacy of high nutrient inputs as described above and evidenced by the high soil Morgan’s potassium and soil Morgan’s P concentrations. Very high soil Morgan’s P concentrations combined with the high volumes of overland flow, due to the low permeability of the clay loam soil in the present study, indicates that this was a site with high risk of TP loss to water (Hart et al., 2004). Overall, annual TP losses estimated from the current study (775 to 918 g ha^{-1} y^{-1} Table 6) would be classified as low to moderate according to Jordan et al. (2012). Furthermore, the TP values in the present study were very much lower than 2000 to 3000 g ha^{-1} year^{-1} from mole drains under grazed grassland reported by Haygarth et al. (1998).

The transport of TP from the soil to water occurred in dissolved and particulate forms. In the present study the greatest losses were in the form of DRP accounting between 0.62 and 0.67 of TP losses to water via the three loss pathways (overland flow, mole flow and ground water flow). Overland flow was the main loss pathway for DRP, accounting for >0.85 of DRP losses across the three treatments, most likely due to the soil P content from the soil upper layers.

Installation of Mole and Gravel Mole improved water infiltration into the soil and decreased the volume of overland flow from these treatments (Table 3) and hence lowered the losses of DRP and TP in overland flow from these treatments. It is well established that most of the P exported from soils is mainly through overland flow (Hart et al., 2004; Sharpley et al., 1999). Furthermore, it is likely that improved infiltration associated with Mole and Gravel Mole facilitated the adsorption of DRP as it percolated through the soil profile (Chardon et al., 1997; McDowell et al., 2001), hence, lowering the losses of DRP (and TP) in mole flow and ground water flow (Table 6). The pH of the soils was from 6.5 to 7.5 (Table 1); in this pH range, the main DRP species are the $H_2PO_4^-$ and HPO_4^{2-}. Under acidic conditions, phosphate sorption is pH driven (Scarseth 1935). The most likely sorption mechanism that could have happened in the current study would be the presence of metal oxides, iron and aluminium hydroxides, poorly crystalline aluminosilicates, which are found within a wide range of soil orders, as well as organo-mineral complexes (Violante et al. 2002). However we did not measured the above components. Finally, the very low concentrations of DRP in ground water flow also indicated that there might be P sorption capacity of the overlying soil layers in this study.

The DRP losses from Gravel Mole were greater than Mole. This can be explained by the improved infiltration capacity by drainage. However, a Langmuir isotherm was conducted to determine the P sorption capacity of the gravel and the surrounding soil following the methodology described by Fenton et al. (2009). Results showed that gravel had a maximum sorption capacity of approximately 0.07 mg PO_4-P kg^{-1}, which was much lower than the P sorption capacity of the soil (Djodijic et al. 2004). Hence the greater DRP losses from Gravel Mole can be partly attributed to the presence of gravel in the Gravel Mole channels that lowered the interaction between drainage water and the soil. Moreover, the channels for the Mole treatment were 0.1 m deeper than the Gravel Mole. This increased the travel distance of the water through the soil and hence allowed greater potential for P-sorption.

Particulate P accounted for between 0.16 and 0.20 of P losses to water via the three pathways. McDowell et al. (2001) also concluded that in grassland overland flow carries relatively little sediment due to minimal erosion. The majority of PP across all the treatments (0.69) was lost through the overland flow pathway. However PP flux in the overland flow was lower in mole and gravel Mole than Control because of lower overland flow and higher mole flow associated with Mole and Gravel Mole.

There was a greater flux of PP in mole flow from Mole than Gravel Mole (Table 5), which can be attributed to the absence of gravel in Mole leaving the walls of the Mole drain channels exposed to a greater degree of erosion than Gravel Mole.

4.2 Nitrogen loss to water

Despite no inorganic fertilizers being applied during this study, the background N in the soil combined with biologically fixed N was able to support a high level of N uptake by the herbage (459 kg ha^{-1}). It can be assumed that much of this N was subsequently recycled in urine and dung by the grazing dairy cows (although this aspect was not investigated in this study).

In contrast to P, improving infiltration by installing the drainage treatments lowered the proportion of nitrate-N and ammonium-N lost in overland flow and increased the proportion lost in mole flow and to ground water flow (Table 5), with the overall result that more nitrate-N and ammonium-N were lost from Mole and Gravel Mole than from Control. This difference can be attributed to greater attenuation and denitrification of nitrate-N in C, whereas drainage and Gravel Mole facilitated the rapid loss of nitrate-N from the soil in mole flow. Both nitrate-N concentrations and fluxes were higher from Gravel Mole than from Mole. This can be partly attributed to the Gravel Mole channels being shallower than Mole channels. Moreover, nitrate-N losses were higher than ammonium-N in mole flow from Gravel Mole. Again, this can be explained by Gravel Mole facilitating a more rapid discharge of water via the mole channels; in this case lowering the travel time and decreasing the extent of denitrification taking place. Similar phenomena was reported by Gold et al. (2001)

that found that artificially lowering the watertable resulted in nitrate-N bypassing areas of high natural attenuation, thus increasing nitrate-N losses.

Most (>0.54) of the ammonium-N was lost to ground water flow. This can be attributed to the impact of the microbial activity on the chemical transformation of N in the soil. Previous studies at this site (Necpalova et al., 2012) reported that biochemical transformation i.e. nitrate reduction to ammonium, is facilitated by the thickness of the saturated zone in the soil profile. This process is called dissimilatory nitrate reduction to ammonium. Soil dissimilatory nitrate reduction to ammonium capacity was likely to have been unaffected by drainage treatment (below drains depth) in the present study, this was shown on the lack of difference between treatments on the ammonium-N losses to the ground water (Table 4 and 5).

Annual nitrate-N and ammonium-N losses in the present study were lower than that found by Monaghan et al. (2002) and are within the range of a previous study on the present site, where losses in the shallow ground water under circumstances similar to the undrained control system in the present study were examined (Necpalova et al., 2012). A recent study at this site, also under undrained conditions, by Burchill et al. (2016) reported annual N losses to ground water (mean ± standard deviation) of 21±8 and 5±2 kg ha^{-1} during 2011 and 2012, respectively. Authors reported a large inter-annual variability most likely affected by the climatic conditions. In the current study cumulative rainfall was similar to the year 2012 (1147 mm), despite this losses in the latter study were greater than annual N losses to water found in the present study. Burchill et al. (2016) concluded that the majority of N was lost from the soil as dinitrogen gas (0.44) followed by ammonia (0.42) whereas N losses (encompassing nitrate, ammonium etc.) to ground water flow accounted for 0.06 of total N losses.

4.3 Phosphorus and nitrogen concentrations in water

In this study the mean concentration of DRP lost via the overland flow and mole flow pathways was 0.41 mg L^{-1}, which is above the threshold of 0.03 mg L^{-1}necessary to avoid eutrophication in water bodies (European Council, 2003). These high concentrations can be explained by the extremely high soil P concentrations at this site.

Mean nitrate-N concentrations reported in this study were very low relative to that reported in other studies; i.e. 15 (range 5 to 21) mg nitrate-N L^{-1}(Sharpley and Syers, 1979) and 6.9 (range 1 to 28) mg nitrate-N L^{-1} (Monaghan et al., 2002). In the present study the mean nitrate-N concentration lost via the various pathways were 0.96 mg L^{-1}, well below the maximum allowed concentration (MAC) of 11.3 mg L^{-1} (European Council, 2000). However, the mean ammonium-N concentration reported in the present study was 1.09 mg L^{-1}, higher than the MAC for ground water, 0.065 mg N L^{-1} for surface water and 0.175 mg N L^{-1} for drinking water (European Council, 2009).

5. Conclusions

Over a full year of observations, we concluded that Mole and Gravel Mole drainage treatments deepened the watertable depth and decreased the volume of overland flow by improving soil permeability. This had direct implications for the interconnectivity of the hydrological pathways and associated nutrient losses in mole flow and to ground water flow. Mole and Gravel Mole drainage treatments increased the extent of nitrate-N and ammonium-N losses, although nitrate-N concentrations remained well below the threshold for drinking water. Ammonium-N concentrations were above the drinking water quality standards. Conversely, Mole and Gravel Mole lowered DRP and TP losses, by enhancing soil water infiltration. Therefore, Mole and Gravel Mole management techniques for improving trafficability and grass utilization are not likely to increase P losses to water, in particular DRP, on farms under similar management to that described in the present study. However nitrate-N and ammonium-N losses to water are likely to be higher, albeit in this study overall annual losses were very low.

6. Acknowledgements

We would like to acknowledge the technical assistance of D. Barrett and the staff at the Teagasc Solohead Research Farm. This research was conducted with the financial support of Department of Agriculture Food and Marine, Project SOGGYLAND (RSF11152) and the Teagasc Walsh Fellowship Scheme.

7. References

Burchill, W., G. Lanigan, D. Li, M. Williams, and J. Humphreys. 2016. A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions. Agriculture, Ecosystems & Environment 220:202-210.

Burke, W., J. Mulqueen, and P. Butler. 1974. Fertiliser losses in drainage water from a surface water gley. Irish Journal of Agricultural Research:203-214.

Chardon, W., O. Oenema, P. Del Castilho, R. Vriesema, J. Japenga, and D. Blaauw. 1997. Organic phosphorus in solutions and leachates from soils treated with animal slurries. Journal of Environmental Quality 26 (2):372-378.

Coulter, S., S. Lalor, C. S. Alex, A. Black, A. Bol, J. Burke, O. T. Carton, B. S. Coulter, N. Culleton, and P. Dillon. 2008. Major and micro nutrient advice for productive agricultural crops.

Creamer, R., I. Simo, B. Reidy, J. Carvalho, R. Fealy, and S. Hallett, Jones, R.,Holden, A., Holden, N., Hannam, J., Massey, P., Mayr, T., McDonald, E.,O'Rourke, S., Sills, P., Truckell, I., Zawadzka, J., Schulte, R.,. 2016. Irish soil information system 2014 [cited 8 February 2016]. Available from http://gis.teagasc.ie/soils/map.php.

Djodjic, F., Börling, K., & Bergström, L. (2004). Phosphorus leaching in relation to soil type and soil phosphorus content. Journal of Environmental Quality, 33(2), 678-684.

Dillon, P., J. Roche, L. Shalloo, and B. Horan. 2005. Optimising financial return from grazing in temperate pastures. Utilisation of grazed grass in temperate animal systems (ed. JJ Murphy):131-147.

European Council. 2000. Directive 2000/60/EC establishing a framework for Community action in the field of water policy. Official Journal of the European Union L 327, 1-73.

European Council. 2003. Water Policy Regulations. electronic Irish Statute Book (eISB) (S.I. No. 722 of 2003).

European Council. 2009. Environmental Objectives (Surface Waters) Regulations electronic Irish Statute Book (eISB) (S.I. No. 272 of 2009).

Fenton, O., M. Healy, M. Rodgers, and D. Huallachain. 2009. Site-specific P absorbency of ochre from acid mine-drainage near an abandoned Cu-S mine in the Avoca–Avonmore catchment, Ireland. Clay Minerals 44 (1):113-123.

Fitzgerald, J., A. Brereton, and N. Holden. 2008. Simulation of the influence of poor soil drainage on grass-based dairy production systems in Ireland. Grass and Forage Science 63 (3):380-389.

Gold, A. J., P. M. Groffman, K. Addy, D. Kellogg, M. Stolt, and A. E. Rosenblatt. 2001. Landscape attributes as controls on ground water nitrate removal capacity of riparian zones: Wiley Online Library.

Hart, M. R., B. F. Quin, and M. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects. Journal of Environmental Quality 33 (6):1954-1972.

Haygarth, P. M., L. Hepworth, and S. C. Jarvis. 1998. Forms of phosphorus transfer in hydrological pathways from soil under grazed grassland. European Journal of Soil Science 49 (1):65-72.

Helsel, 1990, Enviro. Sci. Technol, 24, 1767-1774; DOI: 10.1021/es00082a001

Ibrahim, T., O. Fenton, K. Richards, R. Fealy, and M. Healy. 2013. Spatial and temporal variations of nutrient loads in overland flow and subsurface drainage from a marginal land site in south-east Ireland. In Biology and Environment: Proceedings of the Royal Irish Academy (pp. 169-186). Royal Irish Academy.

Jaccard, J., Becker, M.A., Wood, G., 1984. Pairwise multiple comparison procedures: A review.le. Psychol. Bull. 96, 589.

Jordan, P., A. R. Melland, P. E. Mellander, G. Shortle, and D. Wall. 2012. The seasonality of phosphorus transfers from land to water: Implications for trophic impacts and policy evaluation. Science of the Total Environment 434:101-109.

Keane, T. 1992. Impact of weather on grassland farming, in: Keane, T. (Ed), Irish Farming. Weather and Environment. AGMET, Dublin: pp. 125 – 135.

Kurz, I., C. Coxon, H. Tunney, and D. Ryan. 2005. Effects of grassland management practices and environmental conditions on nutrient concentrations in overland flow. Journal of Hydrology 304 (1):35-50.

McDowell, R. W., A. N. Sharpley, L. M. Condron, P. M. Haygarth, and P. C. Brookes. 2001. Processes controlling soil phosphorus release to runoff and implications for agricultural management. Nutrient Cycling in Agroecosystems 59 (3):269-284.

Monaghan, R. M., R. J. Paton, and J. J. Drewry. 2002. Nitrogen and phosphorus losses in mole and tile drainage from a cattle-grazed pasture in eastern Southland. New Zealand Journal of Agricultural Research 45 (3):197-205.

Necpalova, M., O. Fenton, I. Casey, and J. Humphreys. 2012. N leaching to groundwater from dairy production involving grazing over the winter on a clay-loam soil. Science of the Total Environment 432:159-172.

Peukert, S., Griffith, B.A., Murray, P.J., Macleod, C.J., Brazier, R.E., 2014. Intensive management in grasslands causes diffuse water pollution at the farm scale. J. Environ. Qual. 43, 2009–2023.

Scarseth, G. D. (1935). Mechanism of phosphate retention by natural alumino-silicate colloids. Journal of the American Society of Agronomy.

Schulte, R., J. Diamond, K. Finkele, N. Holden, and A. Brereton. 2005. Predicting the soil moisture conditions of Irish grasslands. Irish Journal of Agricultural and Food Research:95-110.

Shalloo, L. 2009. Milk production costs–Can we compete. Paper read at Proceedings of the Teagasc National Dairy Conference. 18 November 2009, Mullingar, Co. Westmeath (Vol. 18, pp. 19-38).

Sharpley, A., and J. Syers. 1979. Loss of nitrogen and phosphorus in tile drainage as influenced by urea application and grazing animals. New Zealand Journal of Agricultural Research 22 (1):127-131.

Sharpley, A. N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 1999. Agricultural phosphorus and eutrophication. US Department of Agriculture, Agricultural Research Service, ARS-149 42.

Tuohy, P., J. Humphreys, N. Holden, and O. Fenton. 2016. Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. Agricultural Water Management 169:129-139.

Tuohy, P., J. Humphreys, N. M. Holden, and O. Fenton. 2015. Mole drain performance in a clay loam soil in Ireland. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science 65 (sup1):2-13.

Valbuena-Parralejo, N., Tuohy, P., Fenton, O., Burchill, W., Williams, M., Lanigan, G. J., & Humphreys, J. (2019). Greenhouse gas emissions from temperate permanent grassland on clay-loam soil following the installation of artificial drainage. Agriculture, Ecosystems & Environment, 269, 39-50.

Violante, A., Pigna, M., Ricciardella, M., & Gianfreda, L. (2002). Adsorption of phosphate on variable charge minerals and soils as affected by organic and inorganic ligands. In Developments in soil science (Vol. 28, pp. 279-295). Elsevier.

White, M. J., D. E. Storm, P. R. Busteed, S. H. Stoodley, and S. J. Phillips. 2009. Evaluating nonpoint source critical source area contributions at the watershed scale. Journal of Environmental Quality 38 (4):1654-1663.

Figure 1. Location of the study area, experimental sites, groundwater flow direction and open drain. North is upslope position and south is down slope. Hydrological isolation consisted on a 1 m deep by 0.5 m wide ditch filled with gravel (20-30 mm grade). Data presented in the currents study was from treatments, uncrained (C), mole drain 2 (M) and gravel mole drain (GM).

Figure 2. Soil vertical section of Mole (M) and Gravel mole (GM) drainage treatment drainage systems.

Figure 3.(a) Daily precipitation, (b) Effective drainage (ED) and (c) Soil moisture deficit (SMD)values for the period 01/03/14 to 01/04/15 during which the rainfall events were selected. Lines in black in (a) indicate the start of the monitored events.

Table 1. Soil properties at Solohead Research Farm at four different depths. All values are means of at least three determinations. Bulk density (BD), hydraulic conductivity (HD), total nitrogen (TN), total carbon (TC), soil organic carbon (SOC).

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-3})	HD (mm h^{-1})	Total porosity (%)	pH	TN (t ha^{-1})	TC (t ha^{-1})	Total inorganic C (t ha^{-1})	SOC (t ha^{-1})
0 to 10	40	29	29	1.01	0.0012	61.71	6.5	12.7	119.7	2.4	117.3
10 to 30	41	20	39	1.05	0.0020	60.32	6.8	8.8	83.1	2.5	80.6
30 to 60	34	20	46	1.21	0.0016	54.31	7.5	3.3	7.2	0.7	6.5
60 to 80	11	31	58	1.33	0.0028	49.81	7.5	2.4	6.8	0.8	6.0

Table 2 .Pre-event and event rainfall characteristics of the 15 selected rainfall events.

Event (dates)	Event duration (h)	Rainfall during event (mm)	7-day antecedent precipitation (mm)	30- day antecedent precipitation (mm)	Antecedent SMD (mm)	Max intensity (mm/h)	Mean intensity (mm/h)	ED (mm)
1 (08/05/2014 to 09/05/2014)	28	11.2	4.2	68.8	-8.8	5.2	0.42	10.4
2 (06/06/2014 to 07/06/2014)	32	4.2	7.7	91.0	0.5	1.6	0.18	3.1
3 (09/06/2014 to 10/06/2014)	37.5	11.6	11.8	113.2	-9.3	5.6	0.52	12.0
4 (26/06/2014)	19.5	10.2	3.2	40.8	-10.0	4.4	0.52	8.6
5 (07/07/2014 to 08/07/2014)	21	6.0	3.8	69.8	1.7	11.2	0.34	4.0
6 (19/07/2014)	17	18.6	12.0	71.7	-2.2	13.6	1.1	15.3
7 (02/08/2014 to 03/08/2014)	22	8.0	4.0	76.8	-10.0	3.6	0.36	0.7
8 (05/08/2014)	18	7.4	17.2	38.0	-7.2	2.0	0.42	5.8
9 (06/11/2014)	13.5	15.8	22.4	104.4	-3.5	12.4	1.17	5.7
10 (13/11/2014 to 14/11/2014)	38	45.8	43.0	121.0	-10.0	7.2	1.22	45.6
11 (07/12/2014 to 08/12/2014)	29	16.4	3.2	105.6	-10.0	2.4	0.56	4.7
12 (10/12/2014 to 12/12/2014)	28.5	29.4	14.4	120.5	-10.0	3.6	0.98	27.9
13 (14/01/2015)	11	18.0	19.0	89.7	-10.0	5.2	1.62	15.3
14 (15/02/2015)	10	5.4	23.6	59.0	-4.7	2.4	0.38	4.2
15 (12/03/2015)	14	15.0	12.6	102.8	-10.0	2.4	1.06	14.0

ED = effective drainage, SMD = soil moisture deficit.

Table 3. Mean flows rates in overland flow, mole drain flow and discharge to groundwater over the 15 captured rainfall events. Standard error in between brackets. Number of replicates of each treatment (n) are n =4.

Treatment	**C**	**M**	**GM**	**P-value**	**SEM**[†]
Pathway		(mm h^{-1})			
Overland flow	0.16 (0.00)[a]	0.11 (0.01)[c]	0.12 (0.00)[b]	< 0.05	0.003
Mole Drain flow		0.09 (0.00)	0.13 (0.00)	< 0.001	0.001
Groundwater	0.11 (0.00)	0.1 (0.01)	0.08 (0.01)	ns[‡]	0.01

C = un-drained control, M = mole drainage and GM = gravel mole drainage

†Standard error of the mean; ‡not significant
Different letters from each row indicate significantly different.

Table 4. Flow weighed mean concentration of nutrients over the captured 15 rainfall events in overland flow drain flow and groundwater. Standard error in between brackets.

Treatment	**C**	**M**	**GM**	**P-value**	**SEM**[†]
Overland flow		(mg L^{-1})			
TP	0.93 (0.01)	0.92 (0.02)	0.97 (0.03)	ns[‡]	0.02
DRP	0.62 (0.02)	0.66 (0.04)	0.63 (0.03)	ns	0.03
DUP	0.11 (0.03)	0.17 (0.07)	0.17 (0.07)	ns	0.06
PP	0.19 (0.06)	0.09 (0.02)	0.18 (0.06)	< 0.01	0.05
Ammonium-N	0.2 (0.06)	0.14 (0.06)	0.33 (0.08)	ns	0.07
Nitrate-N	0.75 (0.12)	0.65 (0.11)	0.95 (0.21)	ns	0.15
Drain flow		(mg L^{-1})			
TP		0.22 (0.02)	0.2 (0.01)	ns	0.02
DRP		0.04 (0.009)	0.1 (0.01)	< 0.001	0.01
DUP		0.08 (0.03)	0.05 (0.01)	ns	0.02
PP		0.1 (0.021)	0.05 (0.015)	< 0.001	0.02
Ammonium-N		0.65 (0.11)	0.58 (0.07)	ns	0.09
Nitrate-N		1.21 (0.05)	1.55 (0.07)	< 0.01	0.06
Groundwater		(mg L^{-1})			
DRP	0.01 (0.01)	0 (0.00)	0.01 (0.02)	ns	0.01
Ammonium-N	1 (0.14)	1.16	1.12	ns	0.27
Nitrate-N	0.81 (0.55)	1.01 (0.6)	1.06 (0.63)	ns	0.59

C = un-drained control, M = mole drainage and GM = gravel mole drainage. P = Phosphorus, TP = total P, PP = particulate P, DRP = dissolved reactive P and DUP = dissolved unreactive P. TP = PP+ (DRP+DUP). [†]Standard error of the mean; [‡]not significant

Table 5. Mean fluxes product of concentration and flow of nutrients over the captured 15 rainfall events in overland flow, drain flow and groundwater.

Treatment	C	M	GM	P-value	SEM[†]
Overland flow		(g ha^{-1} h^{-1})			
TP	1.52 (0.1)	1.06 (0.086)	1.16 (0.098)	< 0.05	0.1
DRP	1.02 (0.09)	0.76 (0.03)	0.75 (0.03)	< 0.01	0.05
DUP	0.19 (0.03)	0.19 (0.04)	0.2 (0.07)	ns[‡]	0.05
PP	0.31 (0.08)	0.11 (0.02)	0.21 (0.03)	< 0.05	0.04
Ammonium-N	0.33 (0.08)	0.16 (0.02)	0.4 (0.08)	< 0.05	0.06
Nitrate-N	1.2 (0.13)	0.74 (0.094)	1.13 (0.11)	< 0.05	0.13
Drain flow		(g ha^{-1} h^{-1})			
TP		0.19 (0.02)	0.25 (0.06)	ns	0.04
DRP		0.03 (0.01)	0.13 (0.04)	< 0.001	0.03
DUP		0.07 (0.046)	0.06 (0.025)	ns	0.04
PP		0.09 (0.009)	0.06 (0.01)	< 0.05	0.01
Ammonium-N		0.56 (0.08)	0.73 (0.1)	ns	0.09
Nitrate-N		1.04 (0.04)	1.96 (0.08)	< 0.0001	0.06
Groundwater		(g ha^{-1} h^{-1})			
DRP	-	-	-		
Ammonium-N	1.13 (0.38)	1.3 (0.44)	0.86 (0.23)	ns	0.3
Nitrate-N	0.91 (0.37)	1.14 (0.42)	0.81 (0.21)	ns	0.28

C = un-drained control, M = mole drainage and GM = gravel mole drainage. P = Phosphorus, TP = total P, PP = particulate P, DRP = dissolved reactive P and DUP = dissolved unreactive P. TP = PP+ (DRP+DUP). [†]Standard error of the mean; [‡]not significant, - measured but very low/not detected.

Table 6. Total estimated annual losses of nutrients to water, which is the sum of losses in runoff, drain flow and groundwater. Number of replicates of each treatment (n) are n =4.

Treatment	C	M	GM	P-value	SEM[†]
		(g ha^{-1} year^{-1})			
TP	918 (24)^{a}	755 (18)^{c}	853 (13)^{b}	< 0.001	14
DRP	615 (28)^{a}	479 (15)^{c}	526 (14)^{b}	< 0.01	14
DUP	113 (3)	159 (4)	160 (8)	ns[‡]	4
PP	190 (11)	117 (9)	167 (13)	ns	8
Ammonium-N	885 (8)^{c}	1200 (12)^{b}	1225 (14)^{a}	< 0.001	9
Nitrate-N	1293 (33)^{c}	1767 (46)^{b}	2364 (52)^{a}	< 0.001	33

C = un-drained control, M = mole drainage and GM = gravel mole drainage. P = Phosphorus, TP = total P, PP = particulate P, DRP = dissolved reactive P and DUP = dissolved unreactive P. TP = PP+ (DRP+DUP). [†]Standard error of the mean; [‡]not significant. Different letters from each row indicate significantly different.

Highlights

- We measured overland, drainage and ground water flows and the associate soil nitrate, ammonium and phosphorus losses following the installation of mole (M) and gravel mole (GM) drainage systems in a clay-loam soil over 15 rainfall events.
- Drainage treatment deepened the water table and decreased the overland flow.
- M and gravel GM drainage increased losses of nitrate-N and ammonium-N in drainage flow and also losses to ground water. Nitrate-N concentrations were well below the threshold for drinking water and ammonium-N concentrations exceeded drinking water quality standards.
- M and GM lowered total P losses

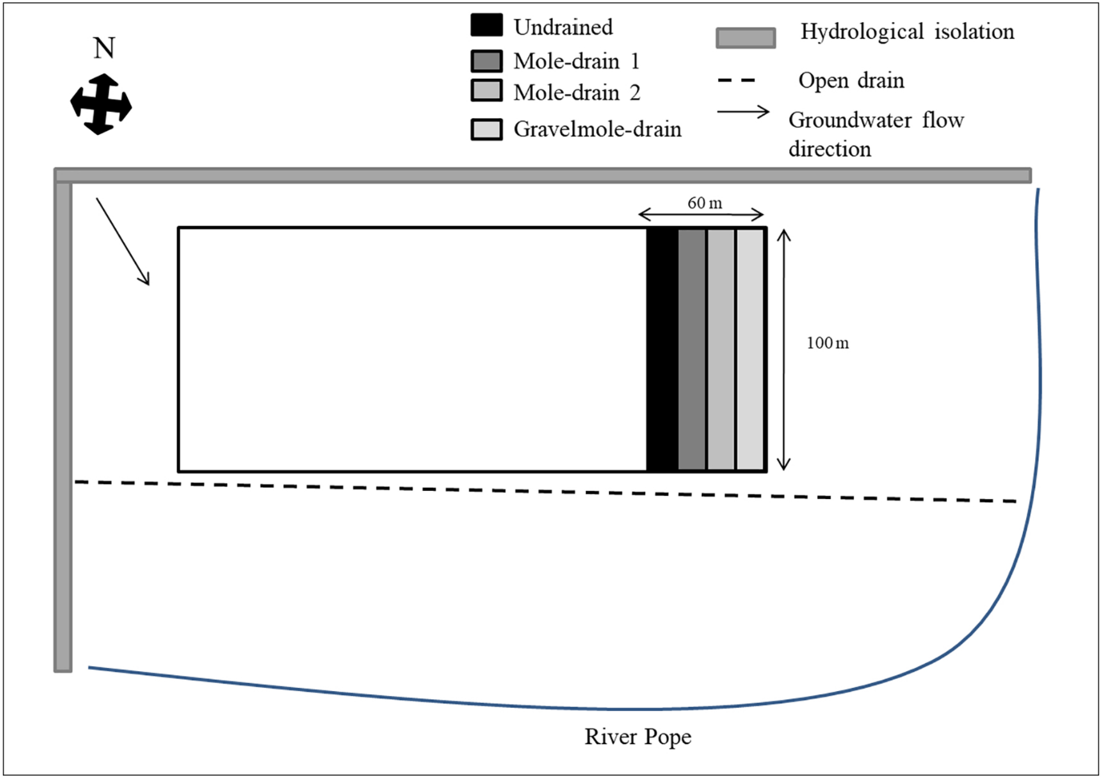
N
Undrained
Mole-drain 1
Mole-drain 2
Gravelmole-drain
Hydrological isolation
Open drain
Groundwater flow direction
60 m
100 m
River Pope

Figure 1

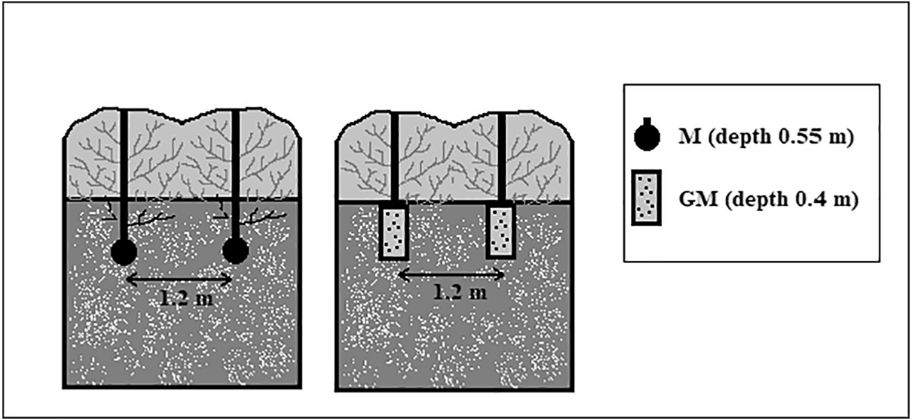

Figure 2

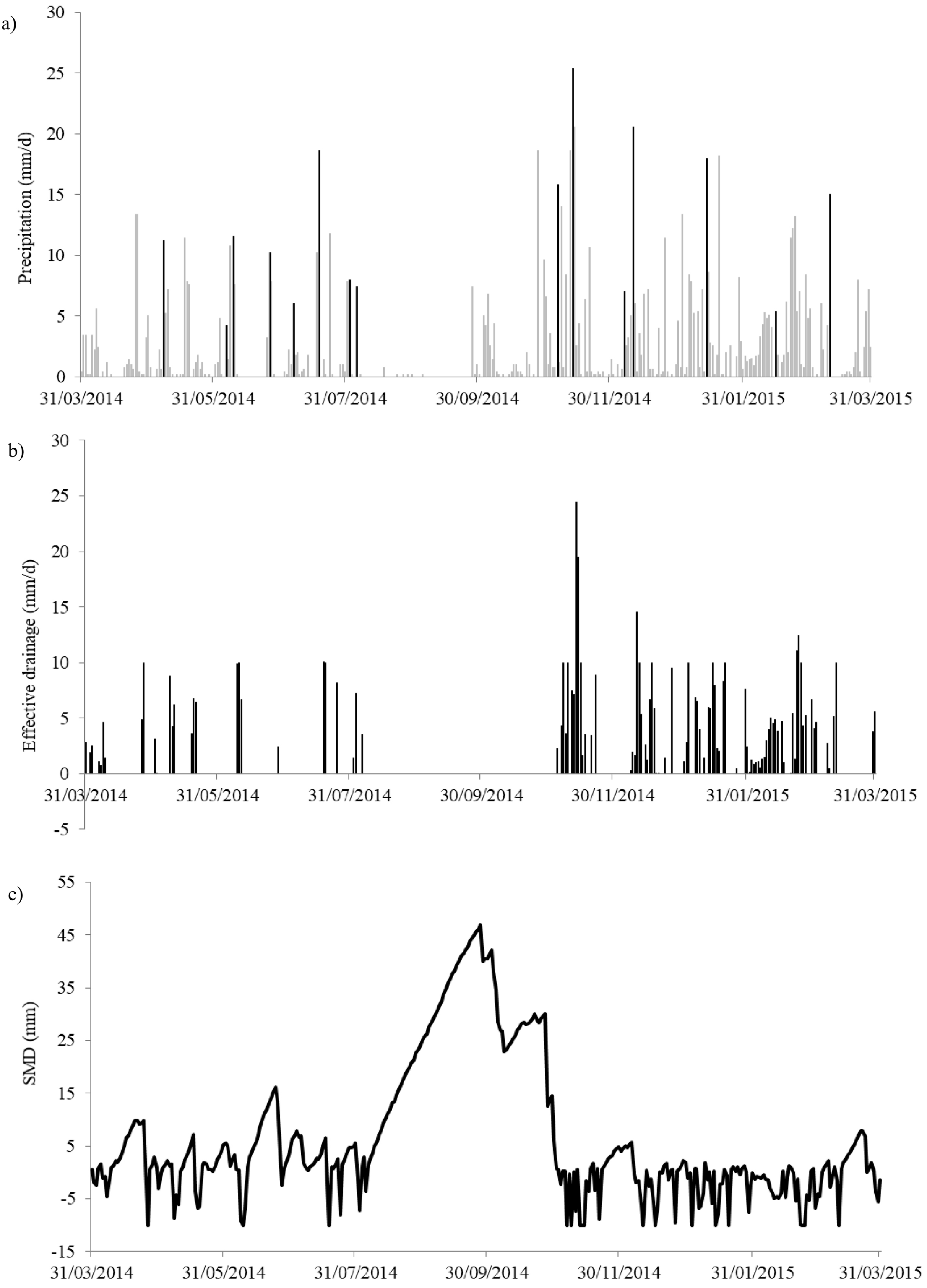
a)
Precipitation (mm/d)
0
5
10
15
20
25
30
31/03/2014
31/05/2014
31/07/2014
30/09/2014
30/11/2014
31/01/2015
31/03/2015
b)
Effective drainage (mm/d)
-5
0
5
10
15
20
25
30
31/03/2014
31/05/2014
31/07/2014
30/09/2014
30/11/2014
31/01/2015
31/03/2015
c)
SMD (mm)
-15
-5
5
15
25
35
45
55
31/03/2014
31/05/2014
31/07/2014
30/09/2014
30/11/2014
31/01/2015
31/03/2015

Figure 3