

A comparison of nutrient losses to waters following pasture renewal by cultivation or direct-drilling

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Abstract

Agricultural soils enriched in phosphorus (P) have been linked to increases in P losses and declining water quality. Cultivation of pastures near sensitive waterways lowers surface soil P and therefore the concentration of P in surface runoff. However, such a practise can increase the mineralisation of organic nitrogen (N), negating this as a mitigation option for N sensitive catchments. A field trial was set up to compare pasture renewal using either direct-drilling or cultivation (which mixed the plough layer to 150 mm) on hydraulically-isolated runoff plots at Tussock Creek near Invercargill, Southland. The trial ran from March to December 2015. Soil P concentrations (0-150 mm depth) decreased in the cultivated plots by about 20%, 8 months after cultivation. Concentrations of nitrate-N in surface runoff and shallow drainage, and P in shallow drainage only, were not different between direct-drilling and cultivation treatments. Cultivation reduced filterable reactive P (FRP) losses in surface runoff by 69% ($P=0.047$) compared to direct-drilled plots. This study showed that mixing P within the plough layer decreased P loss over the 10 months of measurement. Conventional tillage that inverts the plough layer may result in even larger decreases in soil P concentrations. Tillage can therefore be used as a strategy to decrease P loss in small areas where surface runoff is likely, with little risk of increasing catchment-scale N loss. This includes near stream areas, but care must be taken to leave an adequate buffer strip to prevent sediment (and P) loss via erosion of bare soil.

Keywords: phosphorus-enriched soil, cultivation, direct-drilling, runoff, drainage

Introduction

Increasingly, the intensification of farming in New Zealand has resulted in land traditionally used to farm sheep being converted to dairy farming. This change in land use has seen an increase in soil P status, which has been linked to increases in P losses and declining water quality (Hamill & McBride 2003). McDowell *et al.* (2003) showed that losses of filterable reactive P (FRP) increased as the Olsen P concentration increased and suggested that Olsen P concentrations be kept as close as

possible to the agronomic optimum. Where the Olsen P concentration increased to above the agronomic optimum, options to limit, or reduce, the Olsen P concentration of soils quickly are few, as limiting or stopping P fertiliser application can potentially decrease pasture and animal performance.

One mitigation option that has shown promise in lowering soil Olsen P is the cultivation of pastures near sensitive waterways. This distributes P-rich topsoil throughout the plough layer, lowering the concentration of P at the soil surface and in surface runoff (hereafter called runoff: McDowell *et al.* 2010; Dodd *et al.* 2014). However, despite this, the presence of bare ground immediately following the cultivation can result in increased P loss via particulate P in runoff (Butler & Haygarth 2007; Lucci *et al.* 2010). The use of direct-drilling instead of cultivation has been shown to limit particulate P loss in runoff for cropping situations (Soane *et al.* 2012). It has, however, also resulted in increased losses of dissolved P (Ulen *et al.* 2010).

Cultivation can increase the mineralisation of soil organic nitrogen (N) (Whitemore *et al.* 1992). Indeed, Fraser (1995) showed that ploughing of leguminous pastures, even in early autumn, can result in the accumulation of considerable mineral N in the soil profile. However, the use of direct-drilling can result in similar N leaching losses to those from cultivation (Fraser *et al.* 2013). The potential losses of N in drainage water could offset the benefits of the P mitigation option in N-sensitive catchments. While the rapid establishment of arable crops to soak up such excess mineral N has been shown to limit N leaching losses over the winter drainage period (Fraser *et al.* 2013), the effectiveness of establishing permanent pasture for such a purpose has not been tested.

It was hypothesised that renewing pasture via cultivation – resulting in decreased Olsen P in the plough layer/topsoil – would decrease P losses in runoff and drainage, but not increase N losses.

Methods

Site and trial design

The trial was situated on a Pukemutu (Argillic-fragic Perch-gley Pallic) soil (Carrick *et al.* 2000) on a dairy

farm at Tussock Creek, 20 km north of Invercargill, Southland, New Zealand (46°15' S; 168°25' E). The soil was characterised by a fragipan at 30-90 cm depth and was naturally poorly drained, with low permeability in the subsoil and limited aeration during prolonged wet periods. The pasture was predominantly ryegrass/white clover that had been sown some 20-25 years previously.

Plots were installed at the site in November 2011 on slopes between 1 and 2%. Plots were hydraulically isolated from the paddock and neighbouring plots by inserting 25 x 150 mm boards 100 mm into the soil on the boundaries of each plot, allowing 50 mm to extend above the soil surface to direct runoff. The down-slope end of the plot formed a V (140°) with a metal frame complete with a pipe at the centre to direct runoff into a collection system which held 100 litres. Plot size was 10.2 m² with 6 replicates. The layout and size of the plots prevented the use of the normal mole and tile drainage method of measuring drainage losses at this site (Monaghan *et al.* 2016). Drainage samples were, therefore, collected via four teflon cups inserted into each plot to a depth of 30-35 cm (i.e. just above the impermeable fragipan). While the cups were installed shallower than normal for this method of drainage collection, the presence of a fragipan prevented deeper installation. It is recognised that in this soil, the presence of preferential flow pathways will prevent efficient capture of vertical drainage using porous cup samplers (Wang *et al.* 2012). However, the fragipan also causes water to pond and mix above it - potentially improving capture by the cups. It may also lead to the underestimation of N losses via anaerobic conditions and denitrification. The Teflon cups were installed on 27 March 2015, 8 days following the cultivation/direct-drilling of the treatments.

Plots were sprayed with Roundup (Lion) + Pulse penetrant at recommended rates on 3rd March and again on 11th March 2015 to remove the resident herbage. The cultivated plots were rotary-hoed to 150 mm depth and pasture hand-sown (seed broadcast then the plots lightly raked), on 19 March 2015. Direct drilled-plots also were sown on 19 March 2015 by forming slits (10-12 mm depth) with spades (to simulate a disc drill) and hand-sowing the pasture mix into the slits. These slits were spaced ca. 150 mm apart and were positioned across the slope of the plots. The pasture mix consisted of Prospect perennial ryegrass (20 kg) and Kopu II white clover (5 kg) sown at a rate of 20 kg/ha. Runoff and drainage measurements commenced in late April 2015 and pasture production measurements in August of the same year.

Measurements

Profile soil samples (0-75, 75-150 and 150-300 mm depth) were collected before treatment in November

2014, March 2015 and December 2015 and analysed for Olsen P and water soluble P (WSP) concentrations. As the plots were fenced to exclude stock, pasture production was measured by a rising plate meter (Farmworks Precision Farming Systems Ltd., Fielding NZ) using the standard DairyNZ all seasons equation (kg DM = height x 140 + 500; DairyNZ 2008) before the herbage was trimmed off by a rotary mower and clippings discarded.

A daily soil water balance model was used to determine total daily surplus water volumes and soil water deficit values at the site. The conceptual structure of this balance is described by Monaghan *et al.* (2009). Based upon observed drain flows and soil moisture measurements, it was assumed that the ratio of actual evapotranspiration to potential evapotranspiration had a value of 1.0 when soil moisture was between field capacity and a limiting soil water deficit of 50% of plant available water. Thereafter, this ratio decreased linearly to become zero at the permanent wilting point. Potential evapotranspiration data were obtained from the Invercargill meteorological station ca. 20 km south of the study site. Rainfall inputs were measured at the site by a 0.1 mm tipping bucket rain gauge linked to a Campbell Scientific CR10 data-logger. This rain gauge was monitored via telemetry to allow timely decisions on runoff and drainage collection to be made.

The runoff collection system was checked following rainfall (>15 mm) over 12 hours, and samples were collected if runoff had occurred. Due to runoff usually being generated by excess soil saturation, suction was applied to the Teflon cups to obtain drainage samples, at the same time runoff was collected. This did not occur for the first and last runoff events, which resulted from infiltration-excess conditions rather than soil saturation-excess.

Concentrations of total solids (TS) in runoff samples were determined gravimetrically after a known volume of sample had been evaporated to dryness in an oven set at 105°C. All samples were stored frozen until analysed colorimetrically for filterable reactive phosphate (FRP), total filtered phosphate (TFP), total P (TP, runoff samples only), nitrate-N (NO₃-N) and ammonium-N (NH₄-N). Particulate P (PP) for the runoff samples was determined as TP less TFP. Before analysis by ANOVA using GENSTAT v17, all data were tested for normality and log₁₀ transformed if necessary.

Results and Discussion

Rainfall, runoff and drainage volumes

Rainfall for the year was 1053 mm, with 776 mm of this occurring between 19 March when the treatments were imposed and 30 November when measurements ceased. During this period the water balance model indicated there was 380 mm of surplus water. There

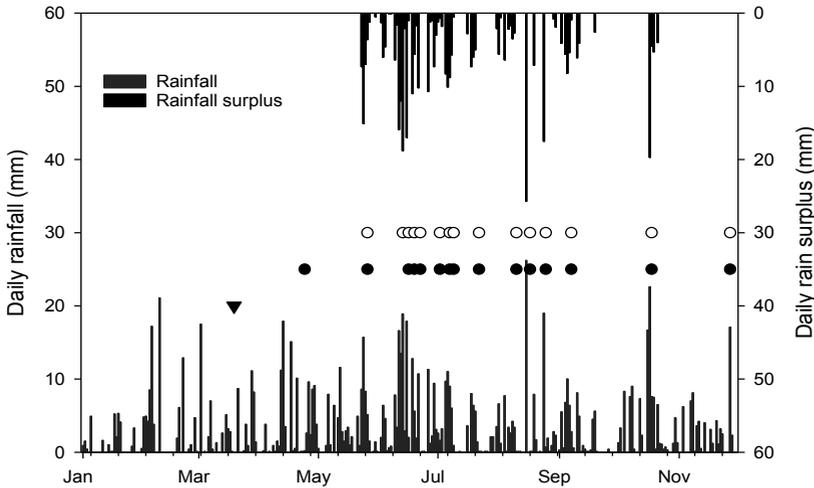


Figure 1 Daily and surplus rainfall at the Tussock Creek trial site. The timing of cultivation/direct-drilling is shown as ▼, while ● indicates the timing of runoff and O drainage events.

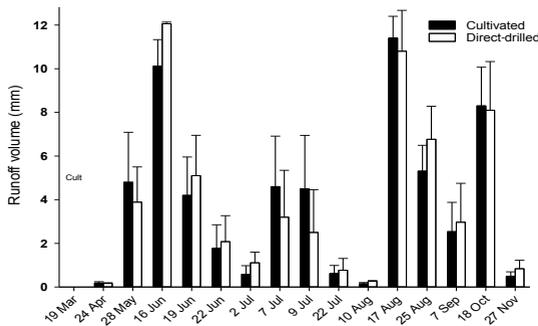


Figure 2 Runoff volumes measured at the Tussock Creek trial site. Bars indicate standard error of the mean ($n=6$).

were 15 runoff and drainage events (Figure 1), with only the first and last runoff events not coinciding with surplus rainfall. There was 58 mm of runoff measured from the cultivated treatments and 61 mm from the direct-drilled treatment. This equates to 16% of the excess rainfall from the water balance model, a figure which compares favourably with previous work at this site that showed runoff accounted for 19% of surplus rainfall (Monaghan *et al.* 2016). The pattern of runoff indicated that 7 of the 15 runoff events exceeded 4 mm per event, with two of these exceeding 10 mm (Figure 2). In total, these seven larger events accounted for 85% of the total runoff.

Pasture production

There were three spring pasture growth measurements (Table 1) with the cultivated treatment producing 15% more pasture than the direct-drilled treatment ($P<0.001$). This difference was more pronounced at the September harvest (21%) than the November

and December harvests (9%). Dodd *et al.* (2014) found increased pasture production following tillage on a similar soil (Mottled Fragic Pallic) to that studied here (Argillic-fragic Perchley Pallic).

Soil analysis

Initial soil sample results, collected in November 2014, were used to randomise the treatments. However, by March when the cultivation occurred, the Olsen P concentration in the topsoil (0-75 mm) had changed, so that

the concentrations in the direct-drilled plots were less than those in the cultivated plots (Table 2; $P=0.018$). While there were no initial differences in the soil WSP concentrations between treatments, concentrations decreased ($P<0.001$) with depth.

The cultivation method used in this study (rotary-hoeing) did not significantly decrease either Olsen P or WSP concentration for the 0-75 mm soil layer (Table 2; December results). This is in contrast with other studies (e.g. McDowell *et al.* 2010), where topsoil P was significantly lowered by cultivation. However, McDowell *et al.* (2010) employed conventional inversion tillage, which would have buried the original P-rich topsoil below 75 mm depth. The cultivation in this study did, however, result in a significant lowering of Olsen P concentrations for the total depth of cultivation (0-150 mm), from 32 $\mu\text{g/mL}$ for the direct-drilled treatment to 26 $\mu\text{g/mL}$ for the cultivated treatment ($P=0.03$). Thus, it would appear that cultivation method and depth are important factors when trying to alter topsoil P concentration.

Table 1 Pasture production for three harvests from sowing to the end of spring 2015 (kg DM/ha). The standard error of difference (SED) is given along with the F-statistic for treatment comparison (bold if significant).

Treatment	30 Sept ¹	4 Nov	17 Dec	Total
Cultivated	2450	2840	3440	5690
Direct-drilled	2030	2600	3160	4940
SED	86	86	109	93
F-statistic	0.004	0.040	0.049	<0.001

¹accumulated since the pasture was sown on 19 March 2015.

Nutrient concentrations and losses in runoff and shallow drainage

When compared to direct-drilling, mixing the plough layer with a rotary hoe resulted in significantly lower FRP concentrations in runoff for 6 of the 15 runoff events (Figure 3). These differences between treatments were mirrored by both TFP and TP concentrations for the same runoff events. However, there were no treatment effects on FRP, TFP or TP concentrations in shallow drainage. Considering that the six significant events accounted for 77% of the total runoff volumes (Figure 2), it was not surprising that cultivation resulted in 39% lower FRP losses ($P=0.047$) and 49% lower TP losses (NS; Table 3) than the direct-drilled treatment. This result is in line with previous work, albeit in a cropping situation, which showed lower FRP losses with normal cultivation compared to direct-drilling (Ulen *et al.* 2010). Particulate P losses from the cultivated plots were not significantly different to those measured from the direct-drilled plots.

Nitrogen concentrations and losses in both runoff and shallow drainage were not increased by cultivation compared to direct-drilling (Figure 4; Table 3). In a study of four soil types, Dodd *et al.* (2014) suggested

that the mineralisation effect following cultivation was likely to be short-lived, and that soil type had a large impact on the amounts of N leached, with the Pallic soil leaching the least amount of N. Considering that there were 36 days between cultivation and the first runoff event, albeit a small one (0.2 mm), and 70 days before any runoff event of note (>3.5 mm), it is likely that the N mineralised by the cultivation had either been re-immobilised, used by the establishing pasture or lost to the atmosphere.

The loss of nutrients, particularly P, via runoff was increased when bare ground was present (Lucci *et al.* 2010). Runoff events that occur in the period between cultivation and pasture establishment can result in increased P loss. Butler & Haygarth (2007) suggested that rainfall intensity, and consequently size of the runoff events before the pasture sward had developed, greatly influenced P loss pathways. Thus, cultivation should be timed to minimise the time the soil is left bare and when runoff events are unlikely.

Conclusions and recommendations

Mixing topsoil via rotary hoe decreased FRP and TP fluxes in runoff by 69 and 49%, respectively, compared

Table 2 Pre- and post-treatment soil Olsen P and water soluble P concentrations ($\mu\text{g/mL}$) results. The standard error of difference (SED) is given along with the F-statistic for treatment comparison (bold if significant).

Treatment	Nov 2014 120 days pre		March 2015 14 days pre		December 2015 200 days post	
	Olsen P	WSP	Olsen P	WSP	Olsen P	WSP
0-75 mm						
Cultivated	43	0.091	37	0.101	37	0.047
Direct-drilled	43	0.086	34	0.094	47	0.055
SED	3.3	0.010	0.9	0.010	4.9	0.015
F-statistic	0.917	0.637	0.018	0.517	0.104	0.604
75-150 mm						
Cultivated	ND ¹	0.035	ND	ND	15	0.025
Direct-drilled		0.037			17	0.029
SED		0.002			2.1	0.004
F-statistic		0.758			0.255	0.425
150-300 mm						
Cultivated	ND	0.023	ND	ND	4	0.014
Direct-drilled		0.025			5	0.016
SED		0.002			0.4	0.001
F-statistic		0.201			0.487	0.141
F-statistic (depth)		<0.001			<0.001	<0.001

¹ ND = not determined

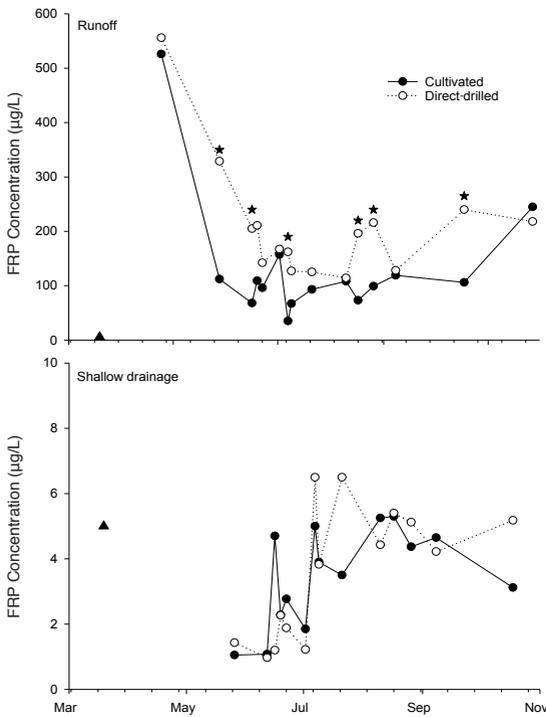


Figure 3 The effect of cultivation and direct-drilling on filterable reactive P (FRP) concentrations in runoff and shallow drainage. Time of cultivation/direct-drilling is given by ▲, while the stars indicate significant differences between treatments ($P < 0.05$).

to direct-drilling. There was no significant increase in N fluxes via runoff or N and P fluxes in shallow drainage, as a result of cultivation. Conventional tillage that inverts the plough layer may result in greater decreases in soil P concentrations and hence P losses in runoff.

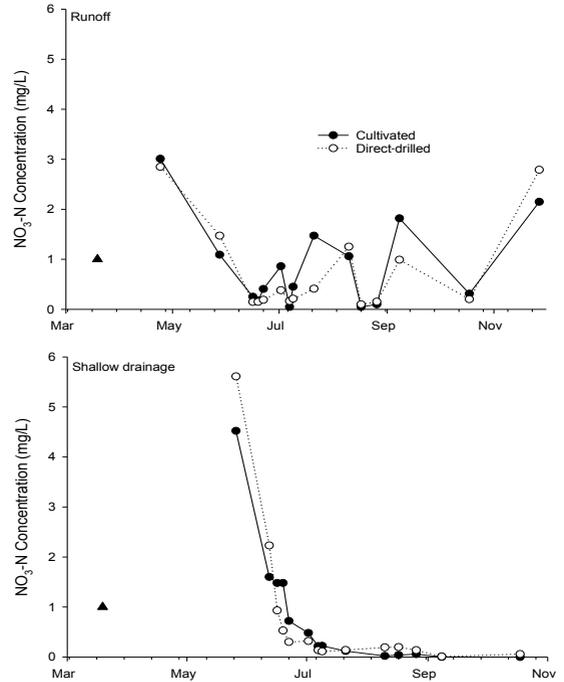


Figure 4 The effect of cultivation and direct-drilling on nitrate-N ($\text{NO}_3\text{-N}$) concentrations in runoff and shallow drainage. Time of cultivation/direct-drilling is given by ▲.

Tillage is therefore recommended as a possible strategy to decrease P losses in areas where runoff is likely. This could occur in near-stream areas where runoff is produced or flows through before entering a stream. However, tillage of near-stream areas should leave a buffer strip to avoid erosion of soil (and associated P) while bare. If tillage is limited to such small areas, it is unlikely to result in increased N losses to water.

Table 3 Mean loads of total solids (TS), particulate P (PP), filterable reactive P (FRP), total dissolved P (TDP), total P (TP), nitrate-N ($\text{NO}_3\text{-N}$) and ammonium-N ($\text{NH}_4\text{-N}$) in runoff and shallow drainage for 8 months post-treatment. The F-statistic for treatment comparison is presented (bold if significant).

Treatment	TS (kg/ha)	PP (g/ha)	FRP (g/ha)	TDP (g/ha)	TP (g/ha)	$\text{NO}_3\text{-N}$ (kg/ha)	$\text{NH}_4\text{-N}$ (kg/ha)
Runoff							
Cultivated	106	93	42	56	149	0.144	0.403
Direct-drilled	105	140	136	152	292	0.160	0.601
F-statistic	0.768	0.253	0.047	0.080	0.147	0.269	0.189
Shallow drainage							
Cultivated	ND ¹	ND	12	29	ND	3.46	0.54
Direct-drilled			15	39		3.77	0.59
F-statistic			0.247	0.119		0.334	0.227

¹ ND = Not determined

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