Phosphorus between soil, soil water and overland flow for established and laser graded, border-check irrigation systems

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Abstract
Agricultural systems contribute to excessive phosphorus (P) additions that are adversely affecting water resources worldwide. The effects of soil disturbance on P exports have not been widely reviewed. In February 2004, four established and four recently laser graded (<4 yrs) border-check irrigation bays on the Macalister Research Farm (38°00'S 146°54'E) were sampled during and after irrigation. Samples were taken at the channel inlet and every 60 m thereafter. Overland flow was sampled at the wetting front and back up the bays, and soil samples were recovered from the sampling locations two days after irrigation. Overland flow was analysed for total P (TP), the soil samples were analysed for soil Olsen P (0-20 and 0-100 mm depths) and soil water, dissolved reactive P (SWDRP) and total P (SWTP) (0-20 mm depth).

There were significant (5% level) differences in soil Olsen P (0-20 and 0-100 mm), SWDRP and SWTP concentrations between lasered and established bays. However there was no significant effect of soil disturbance treatment on overland flow P concentrations. This was a surprising result, as reason would suggest that overland flow P concentration would be reduced as the P rich surface soil is buried by laser grading.

Soil Olsen P (0-20 mm) was related to soil Olsen P (0-100 mm) and both were related to the soil water P (SWP). However, the results suggest that because the slope between SWTP and Olsen P (0-20 mm) was not affected by treatment applied to bays, soil Olsen P (0-20 mm) was better for predicting SWTP than was soil Olsen P (0-100 mm). There was no relationship between SWTP and overland flow TP. This was not unexpected as equilibration of SWP before sampling would be expected to affect the results along with any labile P sources. The experiment suggests that the complexities of P mobilisation from soil to overland flow require further investigation.

Keywords
Phosphorus, soil water, laser graded, irrigation, overland flow

Abbreviations
P – Phosphorus, TP – Total Phosphorus, DRP – Dissolved Reactive Phosphorus, SWP – Soil Water Phosphorus, SWTP – Soil Water Total Phosphorus, SWDRP – Soil Water Dissolved Reactive Phosphorus

Introduction
Excessive nutrient additions, especially phosphorus (P), are adversely affecting Australia's water resources. These nutrient additions are costly as they contribute to algal blooms that have been associated with livestock deaths and human illness (Department of Natural Resources and Environment, 1996). A single bloom in the Darling-Barwon system, stretching for 1000 kilometres, is estimated to have cost $1.3B AUS (Department of Water Resources, 1992).

For P exports to be a problem in receiving waters there needs to be (1) a source of P that is (2) mobilised into water and (3) transported offsite to a location where (4) its adverse effects are expressed (Nash, 2002). In pasture-based grazing systems the highest concentrations of P are found at the soil surface

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where animals defecate, fertilisers are applied and live and decaying organic matter accumulates (Sharpley, 1981). It follows that P exports generally commence with P mobilisation at the soil surface.

Phosphorus can be mobilised in both dissolved (<0.45 μm) and particulate forms (>0.45 μm) and is transported in both surface and sub-surface pathways (Nash and Halliwell, 2000; Nash et al., 2001). Most P is exported from well managed, pasture-based systems in south-eastern Australia in a dissolved reactive form through surface pathways (Nash et al., 2000). As a result there is increasing interest in relating P export potential to soil properties that can be routinely measured, as a method of identifying areas to which appropriate remedial action should be undertaken.

A number of authors have shown relationships between agronomic soil test P (0-100 mm) and dissolved P in either field studies of sub-surface P exports (Heckrath et al., 1995) or model studies (Hesketh and Brookes, 2000). In each case the P concentration in solution remained low until a threshold P concentration (change point) was reached above which P concentrations rapidly increased. The data conformed to a split line model (Maguire and Sims, 2002a, b).

In this study we compared Olsen P (0-20 and 0-100 mm), soil water P (SWP) concentrations (0-20 mm) and overland flow P concentrations from established and recently lasered (<4 yrs) border-check irrigated dairy pastures in the Macalister Irrigation District of south-eastern Victoria. The aims of the study were to (1) determine if an agronomic soil test such as Olsen P can be used to predict SWP and (2) if either Olsen P (0-20 and/or 0-100 mm) or SWP are related to the P in overland flow.

Material and methods

Soil and water samples were collected at the Macalister Research Farm (38°00'S 146°54'E), a dairy farm situated in the Macalister Irrigation District of south-east Victoria. The soil at the research sites was a Natric Grey Sodosol (Isbell, 1996) and carried pastures that contained perennial ryegrass (*Lolium perenne*), white clover (*Trifolium repens*) and assorted invasive species including dock (*Rumex spp*.) and distichum (*Paspalum paspaloides*).

Measurements were conducted on four established and four recently (<4 yrs) laser graded bays (width 30 m, length 240-360 m) following border-check irrigation in February of 2004. Samples were collected from the top of the bays adjacent to the irrigation water inlet and every 60 m thereafter.

Overland flow was sampled when the irrigation wetting front reached a sampling position and at 60 m intervals back up the bay to the irrigation inlet. Vertically integrated overland flow samples were collected across the bay, within 2 m of the sampling point (Nash et al., 2004). A minimum of 14 water columns, each 70 mL, were collected and bulked to give a composite sample for each sampling point.

Soil samples were recovered from two depths (0-20 and 0-100 mm). To allow excess irrigation water to subside, soil samples were collected two days after irrigation. A minimum of 30 cores were recovered from across the bay within 2 m of the sampling point and bulked to provide a composite sample for each bay/sampling point. The soil cores were stored (4^{o}C) in polyurethane bags and transported to the laboratory within 4 hours of collection.

On receipt at the laboratory the bulked soil cores (0-20 mm) were thoroughly hand-mixed prior to a sub-sample (800 g) being used for soil water extraction. Soil water was extracted through centrifugation (3000 rpm) within 12 hours of collection (Toifl et al., 2003). Due to limited volumes of extracted soil water, electrical conductivity (EC) and pH measurements were conducted on samples before a portion was filtered (0.45 μm Millipore) for dissolved reactive phosphorus (DRP) analysis, again within 12 hours of sample collection.

The remaining 0-20 mm and 0-100 mm soil samples were air dried (40^{o}C), ground and passed through a 2 mm sieve. Samples were stored in polyethylene containers at ca. 20^{o}C prior to analysis.

All water samples were analysed for total phosphorus (TP) using alkaline persulphate digestion (Clesceri et al., 1998) followed by flow injection analysis with a Lachat Quickchem 8000 (Zellweger Analytics Inc., Milwaukee) using phosphomolybdenum blue detection chemistry. Soil water extracts were also analysed for DRP within 12 hours of sampling. Soils were analysed for Olsen P using an automated Murphy and Riley method (Rayment and Higginson, 1992).

Statistical analyses
Analysis of variance (ANOVA) was performed on each soil water variable to test the effects of Treatment (lasered verses established pasture) and Position (60, 120, 180, 240 m down the bay), and Position by Treatment interaction. The data were restricted to positions for which there was a complete set of samples, to achieve balance and facilitate stratified ANOVA. The blocking structure for the ANOVA was Bay/Sample (i.e. Sample nested within Bay), identifying the appropriate sampling units as the bay for Treatment, and samples-within-bays for Position.

Analyses of covariance (ANCOVA) were used to investigate relationships between pairs of soil water variables, one (typically, soil water TP) being selected for the dependent variable, and the other (for example Olsen P) being selected for the covariate (or predictor variable). These used the same blocking structure as above to account for the bay and position-within-bay sampling units. ANCOVA's were conducted both with and without treatment structures (Treatment by Position), so as to test the effect of each covariate before and after adjustment for Treatment and Position. Similarly, Treatment and Position effects were tested before and after adjustment for the covariate. In order to examine the possibility of the slope between two variables being dependent on Treatment level, a REML (residual maximum likelihood, or "mixed") model, equivalent to the ANCOVA but allowing for separate slopes, was also performed. All analysis was performed on GenStat 7.1 software (Payne, 2003).

The ANOVA for overland flow TP was similar in structure to the ANOVA's for soil water, but included an additional factor, Front, in the treatment structure, Treatment*(Front.Position), indicating the position of the wetting front at the time of sampling at each position.

ANCOVA was used to examine relationships between overland flow TP and soil water variables. For this the overland flow data were restricted to samples at the wetting front, to ensure a one-to-one matching of soil and overland flow data.

The lines on graphs are simple linear regressions that do not take into account the nested sampling structure, and are included as a guide only.

Results and discussion

Surface soil Olsen P (0-20 mm) vs Root zone Olsen P (0-100 mm)
The average surface soil Olsen P concentration for the sites was 63 mgP/kg. Laser grading had a significant effect (Pr=0.036) on surface soil Olsen P. For the recently lasered and established bays surface soil Olsen P's were 50 and 73 mgP/kg (5% LSD 21), respectively. In both lasered and established bays the surface soil Olsen P increased with distance from the channel inlet (65 to 83 mgP/kg for the established and 41 to 61 mgP/kg for the recently lasered bays).

The root zone Olsen P concentrations were lower than surface soil Olsen P with an average concentration of 27 mgP/kg compared to 63 mgP/kg. There were also differences in root zone Olsen P between lasered and established bays. Unlike the surface soil, where Olsen P's were lower, the root zone Olsen P concentrations were higher in the lasered (31 mgP/kg) than established (24 mgP/kg) bays (5% LSD 3) bays. As with surface soil Olsen P, root zone Olsen P generally increased with distance from the channel inlet for both established (26 to 34 mgP/kg) and lasered (20 to 26 mgP/kg) bays.

The Olsen P in the surface soil and root zone are compared in Figure 1. While a strong correlation existed between P in surface soil and the root zone Olsen P within bays (Pr<0.001), no such relationship existed between bays. This was not unexpected given the changes in Olsen P with distance from the channel inlet and the management of bays as separate entities.

Surface soil Olsen P and root zone Olsen P, although marginal, varied depending on whether bays had been recently lasered (Pr=0.049). This result probably reflected the redistribution of surface soil P during laser grading. Such an explanation is consistent with the relationships presented in Figure 1.

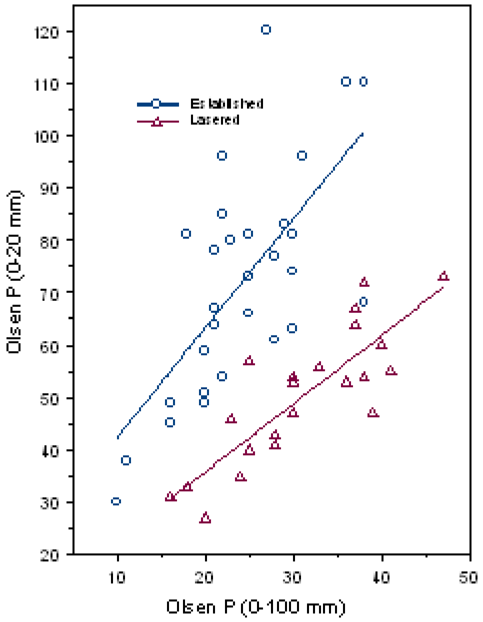

Figure 1. Surface soil Olsen P (0-20 mm) (mgP/kg) vs root zone Olsen P (0-100 mm) (mgP/kg)

Soil water TP (0-20 mm) vs Soil water DRP (0-20 mm)

The average DRP concentrations in soil water was 1.22 mgP/L. There was no significant difference between soil water DRP (SWDRP) for established and lasered bays, with corresponding concentrations of 1.37 and 1.04 mgP/L (5% LSD 0.84).

The average soil water TP (SWTP) concentration was 4.01 mgP/L. Soil water TP concentrations were affected by treatment with lasered and established bay concentrations of 2.05 and 5.58 mgP/L (5% LSD 0.73), respectively. Soil water TP did not significantly vary with sampling position within the bays or between bays within treatments.

Soil water DRP and SWTP are compared in Figure 2. There was a strong relationship between DRP and TP in soil water within bays (Pr=0.001). This was expected as both components were measured on the same soil samples and soil Olsen P varied with distance down the bays. However, no correlation existed between bays.

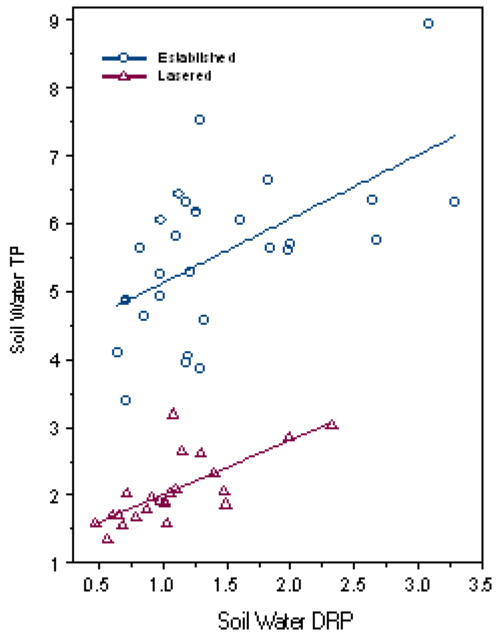

Figure 2. Soil water TP (mgP/L) vs soil water DRP (mgP/L)

Analysis of covariance of SWTP with SWDRP as the covariate indicated that both laser grading (Pr<0.001) and sample position within the bays (Pr=0.032) were significant. For the same DRP concentrations, established bays had higher TP concentrations. This may suggest there is a component in soil water, possibly organic matter, which although at higher concentrations in established bay soil water is removed by 0.45 μm filtration before DRP analysis.

Soil water TP (0-20 mm) vs Surface soil Olsen P (0-20 mm)
The TP of soil water and surface soil Olsen P are compared in Figure 3. A strong correlation existed between TP in soil water and surface soil Olsen P within bays (Pr=0.005), although this relationship did not extend to between bays. The latter result presumably reflects the effect of treatment on surface soil Olsen P.

The relationship between SWTP and surface soil Olsen P between bays was marginal (Pr=0.045) after adjusting for treatment (laser grading). It remained strong within bays after adjusting for treatment by position (Pr=0.002). The slopes between SWTP and surface soil Olsen P were not significantly different for the two treatments.

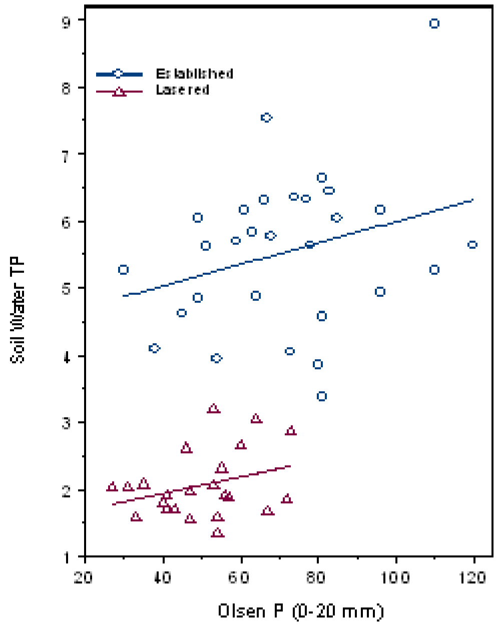

Figure 3. Soil water TP (mgP/L) vs surface soil Olsen P (0-20 mm) (mgP/kg)

Soil water TP (0-20 mm) vs Root zone Olsen P (0-100 mm)
Soil water TP and root zone Olsen P are compared in Figure 4. A strong correlation existed between SWTP and root zone Olsen P both within bays (Pr=0.019) and between bays (Pr<0.001). However, the relationship between bays, was in a negative direction and was totally annulled (Pr=0.201) after adjustment for treatment, which we have already seen had a large impact on SWTP. These data suggest that there are factors associated with laser grading, not evident in Olsen P sampling, affecting SWTP concentrations and that consequently influence the predictive capacity of root zone Olsen P. Due to the variable nature of the data, the existence of a change point cannot be determined.

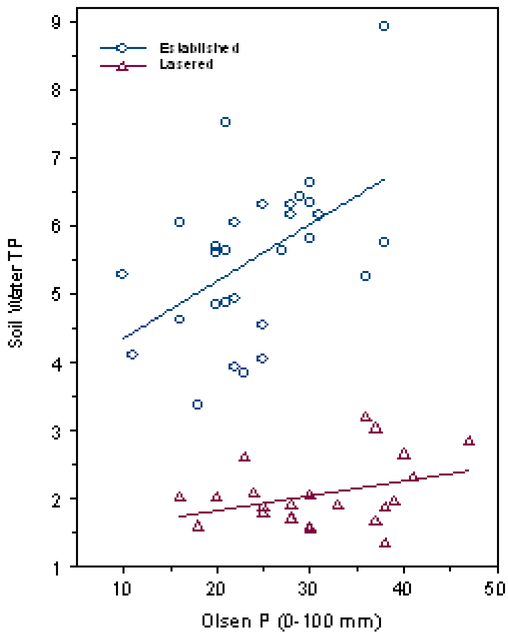

Figure 4. Soil water TP (mgP/L) vs root zone Olsen P (0-100 mm) (mgP/kg)

Overland flow TP vs Soil water TP (0-20 mm)

Overland flow TP concentrations averaged 5.75 mgP/L, which includes samples collected at and behind the wetting front. Laser grading did not significantly effect overland flow TP concentrations of lasered (5.03 mgP/L) and established (6.40 mgP/L) (5% LSD 1.61) bays. However, overland flow TP concentrations were related to both the sampling point within the bay and sampling position in relation to the wetting front of the irrigation water. Presumably as water moves down the bay the wetting front accumulates labile P and overland flow TP concentrations decrease with distance behind the wetting front.

Soil water TP and overland flow TP at the wetting front are compared in Figure 5. There is no significant relationship between soil water and overland flow TP. This was not unexpected due to the time difference between overland flow and soil water sampling. This finding highlights sampling difficulties in obtaining a soil water sample that is representative of overland flow.

Sampling soil water two days after irrigation allows time for the soil and soil water to establish equilibrium. During an irrigation event, equilibrium may not occur as overland flow may remove P at a higher rate than P can be mobilised from the soil. In addition, high P water at the wetting front infiltrates the surface soil at a rate and depth dependant on the soils hydrologic properties (Nash et al., 2004). Water may infiltrate the soil to a depth greater than the 0 to 20 mm cores used from soil water extraction. The soil water deficit used as a basis for irrigation scheduling was 50 mm. Hence, P extracted from soil water (0-20 mm) may not give a true indication of P in overland flow and soil water relationship.

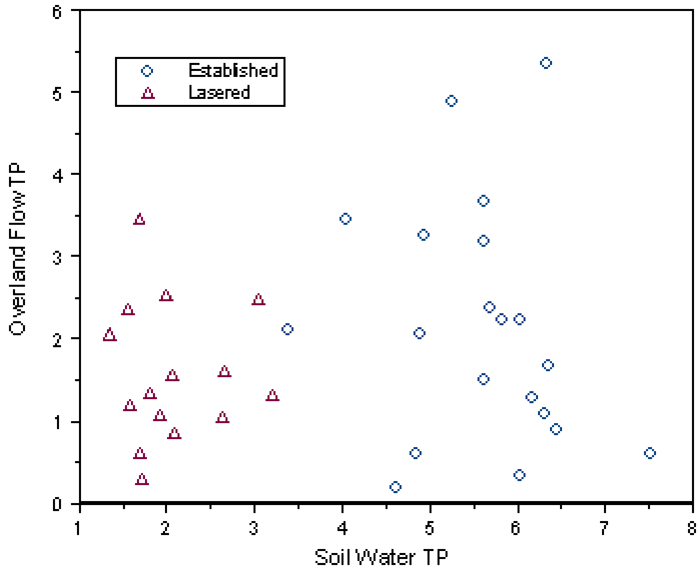

Figure 5. Overland flow TP (mgP/L) at the wetting front vs soil water TP (mgP/L)

Concluding discussion

This study suggests laser grading affected soil Olsen P and SWP concentrations. However, in this study laser grading had no significant effect on overland flow P concentrations. This is a surprising result as intuitively laser grading, which would bury phosphorus rich surface soil, would be expected to lower overland flow P concentrations. However, as the overland flow concentrations from the established pastures were significantly lower than previous studies (Nash and Clemow, 2003; Nash et al., 2004), further investigation is required to confirm these results.

The lack of a relationship between SWP and overland flow P was not unexpected. The SWP is likely to have reflected the solution in equilibrium with the soil. However, the soil water P reflects labile P that was mobilised at the wetting front, the rate of P diffusion from the soil and the dilution of P behind the wetting front. Unfortunately there appears to be few options for relating overland flow P to soil parameters in one off field studies. The option of using a rainfall simulator is being investigated but has inherent difficulties in replicating dissolution processes that are time dependant (Nash et al., 2002).

Surface soil Olsen P (0-20 mm) and root zone Olsen P (0-100 mm) were highly correlated within bays. Soil Olsen P measurements were both affected by laser grading, decreasing soil surface Olsen P and increasing root zone Olsen P, consistent with redistribution of P through the soil profile. Soil water TP was affected by laser grading, and a relationship between SWTP and Olsen P was evident within each treatment. This was true for both surface Olsen P and root zone Olsen P. The slope of the relationship between SWTP and root zone Olsen P depended on treatment, whereas a similar slope was observed for the relationship between SWTP and surface Olsen P. This suggests that the 0-20 mm samples are possibly more useful for predicting P concentrations in soil water (0-20 mm), but factors including soil disturbance also need to be taken into account.

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