Phosphorus export between the paddock and the farm boundary

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Abstract

Phosphorus (P) export from agricultural land contributes to the eutrophication of inland water systems and the development of algal blooms. Phosphorus export between the paddock and farm scales on an irrigated dairy farm in the Macalister Irrigation District, southeastern Australia, was investigated using paddock, farm section and whole farm scale monitoring data. A consistent decrease in P concentrations and loads (ca. 30% decrease in total P) was observed between the paddock and farm section over the study period, while P export from the farm was reduced by up to 98% at the whole farm scale due to installation of a runoff reuse pond.

The reduction in P concentrations and loads observed between the paddock and section scales suggests that P does not behave as a conservative solute during transport through the drainage network, at least for the monitored paddocks. The potential for P uptake and release in drains and likely impacts of different management strategies was investigated using a mathematical model of P transfer in a farm scale drain. While P uptake by bed sediments and P release by plant material was observed in a farm scale drain, the available management strategies are costly and modelling in a farm drain suggests that P export may only be reduced by 10-20%.

Key Words

Spatial scale, surface runoff, overland flow, drains.

Introduction

Inland water systems have an inherent value, both environmentally and to the community through commercial fishing, tourism, recreation and their aesthetic appeal. Phosphorus (P) contributes to eutrophication and the development of algal blooms, which negatively affect these important assets (Atech Group 2000). Phosphorus entering inland water systems comes from a range of sources within a catchment, including dryland and irrigated agriculture. For example, of the P entering the Gippsland lakes in south-eastern Australia, 53 tonnes or 23% is estimated to come from the Macalister Irrigation District (Grayson and Argent 2002).

Research into P export from agricultural land has focussed predominantly on the paddock scale: at this scale the rates of P export are a function of physical properties (e.g. soil type, infiltration rate and slope), climatic factors (e.g. rainfall volume and intensity), and management factors (e.g. soil cover, organic matter accumulation, nutrient additions and irrigation) (Nash 2002). However, P exported at the paddock scale is not necessarily transported through the catchment, with concentrations and loads often an order of magnitude less in streams. For example, in the Macalister Irrigation District (c.a. 58 000 ha) P loads decrease between the paddock and stream by 5:1 to 15:1, based on paddock scale loads of 5-15 kg ha^{-1} P (Barlow 2003) and catchment scale loads of 1 kg ha^{-1} P (Grayson and Argent 2002). Similarly in the Goulburn Broken catchment (northern Victoria, Australia) ratios of 2:1 to 22:1 have been estimated between the paddock and catchment scales (HydroTechnology 1995).

Developing a scientific basis that connects P export from paddock to catchment scales is important for effective P management. Farms represent the largest single management unit in agricultural catchments and are a likely scale at which regulatory conditions may be set. Thus, the whole farm is an important management scale for understanding potential catchment-scale impacts of P exported from a paddock.

This paper investigates phosphorus export at the paddock, farm-section and whole farm scale using two years of data collected from a commercially operated dairy farm in the Macalister Irrigation District, as well as a mathematical model of P movement in drains. Specifically, the paper investigates P transport between the paddock and farm boundary, including the effects of drainage systems and reuse ponds on P exported at the whole farm scale.

Methods

Phosphorus export at the paddock, farm-section and whole farm scale was investigated on the Macalister Research Farm (MRF), southeastern Australia (38°0'S, 146°54'E). The MRF is a commercially operated dairy farm that consists of 80 ha of irrigated perennial pasture which uses a water right of ~270 ML of channel water and ~195 ML of groundwater (~6 ML ha^{-1}) per annum.

The layout of the MRF enabled paddock, farm-section and farm scale monitoring to be conducted in a nested design (Figure 1), incorporating different irrigation practices on the different farm sections. The irrigation treatments were: border-check irrigation using a mixture of channel water and dairy shed effluent (S-1), border-check irrigation using channel water (S-3) and border-check irrigation using a combination of channel and reuse water (S-2 and S-4). Three paddocks (P-12, P-28 and P-29) and three farm-sections (S-1, S-3 and S-4) were used to investigate surface runoff and P export at the two spatial scales. Surface runoff from the farm sections was stored in the reuse pond, and recycled onto S-2 and S-4. Measurement of water and P draining into and out of the 5.1 ML capacity reuse pond allowed the effect of a well managed reuse system on farm scale P export to be investigated.

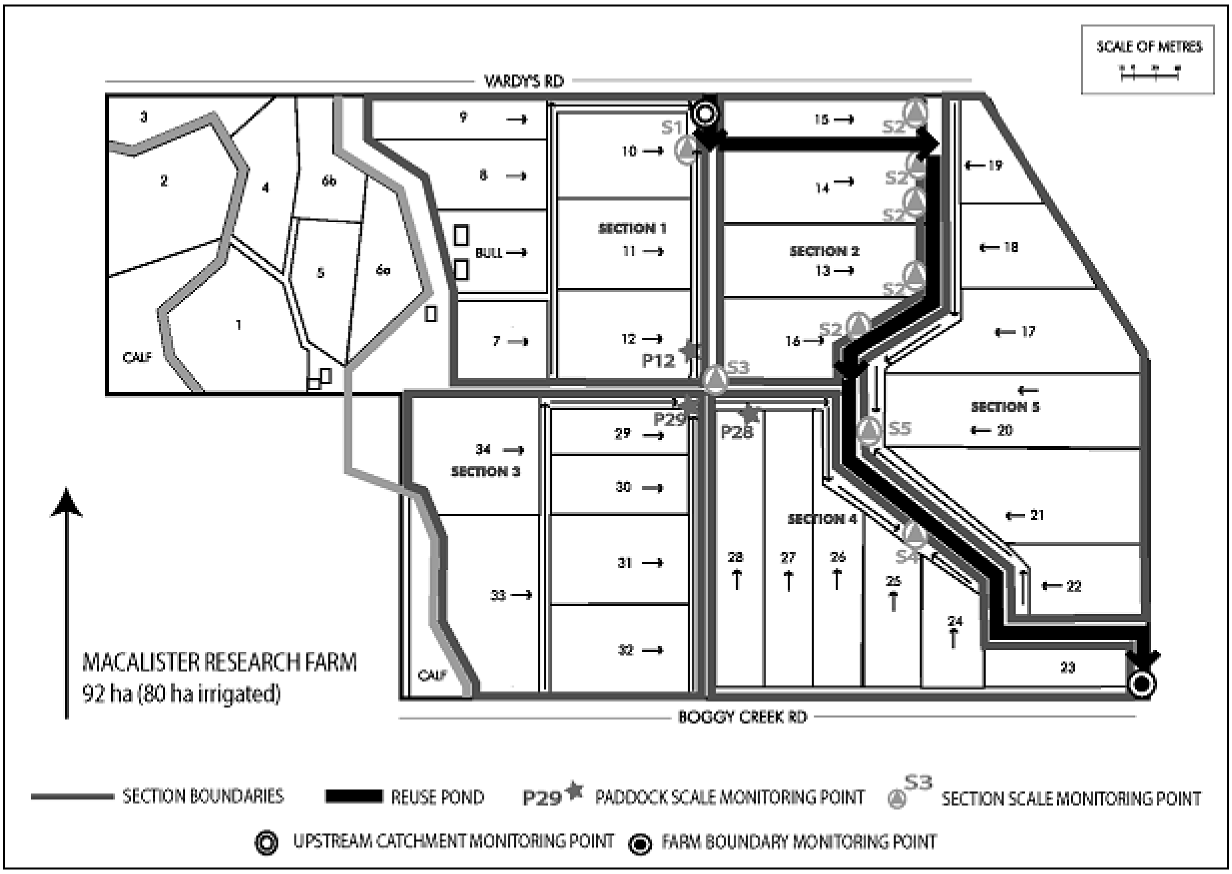

Figure 1. Schematic diagram of the layout of the MRF, showing the monitoring points at the paddock, farm-section and farm boundary. Arrows indicate the direction of water flow on the paddocks and in the drains and reuse pond.

Surface runoff at the paddock and farm-section scales was measured using RBC flumes (Clemmens *et al.* 1984) and ISCO (ISCO Inc. U.S.A.) storm monitoring systems comprising a model 3700 automatic sampler, model 4230 bubbler flow meter and model 674 rain gauge. Water and P entered the reuse system from S-1, S-2, S-3, S-4 and S-5 monitoring points as well as the inlet to the farm (Figure 1), all of which were monitored using RBC flumes and ISCO storm monitoring systems. The farm outlet, which measured drainage from the reuse pond, was monitored using 2×900-mm rectangular weirs and a 60° Vnotch weir combined with an ISCO storm monitoring system. The monitoring system provided flow data with one-minute recording and between 2 and 30 water samples per event (where an event was >100 kL).

Water samples were analysed for total P (TP) using an alkaline persulphate digestion and molybdenum blue chemistry (Murphy and Riley 1962), with the samples analysed on a LaChat Quickchem 8000 flow injection system (Zellweger Analytics Inc. USA). Phosphorus concentration (mg L^{-1}) and flow (L) data for individual storm events were combined to determine the load of P (kg) exported during an event.

Analysis of paddock and farm-section scale concentrations and loads

Comparisons between the paddock and farm-section scales were conducted using equation (1), where the concentration or load of P at the section scale was a function of the section area ($A_{section}$), the concentration or load of P at the paddock scale ($P_{paddock}$) and a scaling factor (van Noordwijk, 1999).

$$P_{\sec tion} = A_{\sec tion} \cdot \left(\frac{1}{A_{\sec tion}} \right)^{0.5 \cdot s} \cdot P_{paddock} \tag{1}$$

The scaling factor (s) was calculated so that $P_{section}$ equalled the concentration or load measured at the farm-section scale (S-1, S-3, S-4). The scaling factor was calculated using yearly averages (3 sections × 2 years) as well as individual runoff events over the 3 year period (3 sections × 2 years × 10 runoff events). Student t-tests were performed in Genstat (6th edition, Lawes Agricultural Trust), to determine whether the calculated scaling factor (s) was significantly different from 2 (i.e. paddock and section scale concentrations and loads were significantly different).

Modelling P transfer in irrigation drains

A model of P transfer in irrigation drains developed from field and laboratory data collected from the MRF (Barlow 2003; Barlow *et al.* 2004; Barlow *et al.* 2003), was used to describe P transfer in a farm drain over 12 months. A detailed description of the model may be found in (Barlow 2003).

Flow in the drain was modelled using a modified form of the volume routing equation (Fenton *et al.* 1999), with a numerical solution based on an advective finite difference scheme. Using Manning's roughness coefficients estimated from the literature, the flow model predicted flow rates and flow volume in a 180m long drain with less than 5% deviation from measured values.

Phosphorus transport with water was described using a simple advective equation where the velocity of water movement determined the transport of P. The net uptake or release of P by bed sediments and plant material were described by individual rate equations. Phosphorus uptake and release by sediments was described using the Elovich equation (Chien and Clayton 1980; House *et al.* 1995), and P release from plants was described using a hyperbolic equation (Havis and Alberts 1993; Schreiber 1999). Phosphorus concentrations and loads in the drain were modelled with less than 10% variation between measured and predicted values over 180 m long drain. By altering the coefficients to represent drain conditions, it was possible to investigate the changes in P concentrations and loads in response to different management scenarios.

Results

Annual flow weighted P concentrations (2.2 - 8.1 mg L^{-1} P) were environmentally significant compared to the 90th percentile water quality target of 0.12 mg L^{-1} P in the receiving streams (EPA 1995). The annual loads (2.5 – 15.3 kg ha^{-1} P) exported at the paddock and farm section scale were significantly higher than estimated catchment scale loads for the Macalister Irrigation District of 1 kg P/ha (Grayson and Argent 2002).

At the paddock scale, annual flow weighted P concentrations varied between paddocks and years (Table 1) ranging from 3.8 - 8.1 mg L^{-1} P. Variability was greater between individual storm events than between paddocks and years, with concentrations for individual events ranging from 0.70 – 28.9 mg L^{-1} P. The variation between storms and years was an expected response to the many variables affecting P concentrations and loads over time including land management and environmental conditions.

Concentrations of P in the applied irrigation water increased from the channel water applied to P-29 (ca. 0.07 mg L^{-1} P), to the reuse water applied to P-28 (ca. 2.4 mg L^{-1} P) and the mixture of dairy shed effluent and channel water applied to P-12 (ca. 5.9 mg L^{-1} P). However, the quality of water applied to the paddock did not appear to affect P concentrations and loads measured in surface runoff. For example, in 2001, the water applied to P-12 and P-28 had an average concentration of 4.8 and 1.3 mg L^{-1} P respectively, while the runoff water from the same sites had an average concentration of 7.1 and 8.1 mg L^{-1} P respectively.

Table 1. Annual flow weighted average phosphorus concentrations and annual phosphorus loads exported at the paddock scale.

Paddock	Year	Water (ML ha^{-1})	TP (mg L^{-1})	TP range (mg L^{-1})	TP (kg ha^{-1})
P-12	2001	2.2	7.1	4.8 - 28.9	15.3
	2002	2.0	7.3	3.6 - 15.9	14.8
P-29	2001	0.9	5.3	0.7 - 14.6	4.6
	2002	1.0	3.8	2.4 - 6.0	3.9
P-28	2001	1.7	8.1	1.6 - 27.7	13.8
	2002	2.2	6.5	3.0 - 32.1	14.4

Table 2. Annual flow weighted average phosphorus concentrations and annual phosphorus loads exported at the farm-section scale.

Section	Year	Water (ML ha^{-1})	TP (mg L^{-1})	TP range (mg L^{-1})	TP (kg ha^{-1})
S-1	2001	2.2	6.2	0.7 – 21.6	14.0
	2002	1.9	4.1	1.8 – 9.1	7.8
S-3	2001	1.2	4.8	0.1 – 14.4	5.7
	2002	1.1	2.2	0.3 – 3.4	2.5
S-4	2001	1.9	3.6	1.4 – 9.8	6.7
	2002	1.8	4.3	1.7 – 8.6	7.7

The results from the farm-section scale generally reflect those from the intensively monitored paddocks (Table 2), with concentrations and loads of water exported of the same order of magnitude. However, there was a consistent decrease in P concentrations and P loads between the paddock and the farm-section scale. To investigate whether the decrease in P export between the paddock and farm-sections scales was significant, a scaling factor (*s*), was calculated (equation 1): note that $s=2$ suggests that concentrations or loads are the same at the paddock and farm-section scale.

Phosphorus concentrations decreased between paddock and farm-sections with a mean scaling factor of 2.33 (s.e.=0.069, n=6) for the annual flow weighted average TP concentrations (Table 6), which was significantly greater than 2 ($p=0.006$). A similar result was obtained when the scaling factor was calculated for individual flow events ($s= 2.31$, s.e.=0.035, n=60). The significant decrease in P concentrations may have been the result of dilution from sub-surface water, management factors within the farm-section or P cycling during transport from the paddock to the section outlet.

A similar analysis revealed a significant decrease in P loads (kg ha^{-1}) between the paddock and farm-section scales. With a mean scaling factor of 2.35 (s.e.=0.080, n=6) and 2.39 (s.e.= 0.079, n=60) for yearly load (Table 6) and individual events, respectively, the scaling factors were significantly greater than 2 ($p=0.026$). These results were consistent with the concentration data and suggest that dilution is unlikely to explain the decrease in concentration between spatial scales.

These results also indicate that paddock scale P losses may not be representative of P export at larger scales. Management practices and P transformations during transport (e.g. Barlow et al. 2003) are 2 factors that may affect P concentrations and loads between the paddock and farm-section scales.

Phosphorus transfer in an irrigation drain

Previous work has shown that P concentrations and loads change significantly during drainage water transport (Barlow *et al.* 2003), depending on the design and management of the drain system. The dominant drain conditions on the MRF during the 2 year monitoring period were either pasture-based drains that were managed as a part of the paddock, or drains with weed growth that were intermittently sprayed with herbicides.

Modelling of P transfer down a 180m pasture-based drain suggested an average 4% decrease in P loads between the top and bottom of the drain over 12 months. However, in the farm sections on the MRF there were over 550m of drain in each section, so assuming an additive effect on P export a 12% reduction in P export may be expected in the farm section. For a drain with a management cycle of bare earth, weed growth and herbicide application the model predicted a decrease in P loads of 9 % over a year, equivalent to a 24% reduction if the reduction is additive over 550m of drain. Assuming 5-10% error in the model predictions, the actual effect of plant based drains on P export was probably minor. While a vegetated drain is unlikely to significantly reduce P export between the paddock and farm boundary, bare-earth drains may act as P sinks due to the P sorption capacities of sediments. Modelling of P transfer along a bare earth drain suggested that a significant reduction in P transfer (approximately 20 % over 180m) might occur.

Maintaining a bare-earth drain through regular herbicide application or excavation may reduce farm scale P export. However, the cost of management options and the increased risk of soil erosion in bare-earth drains suggest that this is not an attractive P export reduction strategy.

Phosphorus at the farm scale

Because soluble P is difficult to remove from drainage water, recycling of surface runoff is a potentially important management strategy to reduce P export into inland water systems. The concentration of P leaving the reuse pond and farm were similar in magnitude to both the paddock and farm-section scales and more than an order of magnitude above the stream target values for the MID (0.12 mg L^{-1} P 90th percentile, EPA 1995). However, the reuse pond on the MRF significantly reduced water and P export at the farm scale. Of the water and P entering the reuse pond in the 2001 and 2002 seasons respectively 41 and 98% of water was reused on the property (Table 3), while 48% and 98% of the P was reused on the property (Table 3). Differences in P export from the property were a function of reuse management during the irrigation season, as well as the occurrence of rainfall runoff from pastures when the reuse pond was already full after an irrigation.

Table 3. Annual flow weighted concentrations and loads of phosphorus into and out of the farm reuse pond.

Year	Water (ML)	TP concentration (mg L^{-1})	TP load (kg)
Water entering the reuse system (including the upper catchment)			
2001	129	5.4	697
2002[a]	97	3.7	359
[b]	221	1.8	398
Water exiting the reuse system (farm scale export)			
2001	75	4.8	360
2002	4	2.1	8.4

[a] bore water not included

[b] total inputs into the reuse system

Concluding discussion

Phosphorus export from irrigated dairy pastures has been shown to be environmentally significant at the paddock, farm-section and whole farm scales, with concentrations more than an order of magnitude above the stream target values for the MID (0.12 mg L^{-1} P 90th percentile, EPA 1995).

We found a significant decrease in the concentrations and loads of P exported between the paddock and farm-section scales. While P uptake in the drainage network may account for some of the reduction in P export, the available management strategies are costly and are only likely to provide a 10-20% reduction in P export.

Significantly, the data presented in this paper suggest that upon mobilisation at the paddock scale, it is difficult to remove P from the drainage water. A well managed farm reuse pond presents an effective management option for reducing P export at the farm scale, with 48 and 98% reduction in P export recorded over 2 consecutive years.

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