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Using the Provenance of Sediment and Bioavailable Phosphorus to Help Mitigate Water Quality Impact in an Agricultural Catchment

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Abstract

The quality and health of surface waters can be impaired by sediment and sediment-bound phosphorus (P). The Waituna Lagoon catchment in southern New Zealand has undergone agricultural intensification that has been linked to increases in sediment and sediment-bound bioavailable P (BAP) in the lagoon. Time-integrated samplers trapped suspended sediment from the water column, and their geochemical signature was compared with likely sources (stream banks, stream beds, topsoil, and subsoil) in each of the lagoon's contributing streams and rivers. The proportion of BAP, but not necessarily total P, within trapped sediment was much greater in samples from the Moffat and Carran Creeks than from the Waituna Creek, probably due to the erosion of organic-rich soils that had little capacity to retain P compared with the more mineral soils of the Waituna Creek. Annually, most BAP and sediment came from bank erosion, and strategies such as fencing out stock should focus on minimizing this throughout the catchment. However, when considering losses in space and time relative to the impact on the Waituna Lagoon, strategies the Waituna Creek catchment should also minimize contributions from topsoil in winter-spring, whereas in the Carran and Moffat Creek catchments strategies need to decrease P inputs (e.g., effluent) to Organic soils likely to lose much BAP in summer-autumn when the impact on the Lagoon is quickest. This study highlighted the need to identify sources and timings of BAP and sediment loss before recommending mitigation practices, which without this information may be slow or not succeed.

Core Ideas

- The water quality of coastal lagoons is affected by sediment and P inputs.
- Knowing the provenance of sediment and BAP can help target strategies to mitigate loss.
- Organic-rich soils lost more BAP but less sediment than mineral soils.
- Mitigating erosion and P form mineral soils should focus on stream banks and topsoil.
- Losses from Organic soils were from many sources; overall P inputs should be lowered.

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The management of eutrophication in lakes, reservoirs, and coastal lagoons largely centers on mitigating phosphorus (P) and nitrogen inputs from contributing streams and, at times, groundwater (McDowell et al., 2015). Among the P fractions commonly measured in freshwaters, it is well established that orthophosphate, reported as soluble, dissolved, or filtered (molybdate) reactive P (FRP), is immediately available to algae (Berman, 1988). Furthermore, many researchers consider filtered, but unreactive, P to be available (e.g., Hatch et al., 1999). In contrast, P bound to particles (i.e., particulate P [PP]) must be released through enzymatic or physical processes before it is available to algae (McDowell et al., 2004). Hence, FRP is measured to assess the potential for algal growth in fast-flowing streams and rivers (Biggs, 2000), and total P (TP) is measured to assess the risk of algal growth in lakes, reservoirs, lagoon ponds, and marshes with high residence times (i.e., lentic systems) (Chapra, 1997). However, it is unclear what proportion of PP is bioavailable.

Methods to determine the bioavailability of PP (BAP) include chemical fractionation that operationally defines a proportion of PP as BAP by correlation with the growth of algae under laboratory and field conditions (e.g., Ekholm and Krogerus, 2003) and bioassays where the growth of algae is measured when subjected to known quantities and forms of P either in the laboratory or field (e.g., Francoeur et al., 1999). Both chemical and biological methods are subject to criticism, such as the availability of P to different algal species (Jones, 1998), but both provide more information about the potential impact of PP in lentic systems than orthophosphate alone (Jansson et al., 2012).

Studies have shown BAP concentrations vary according to land use (Ellison and Brett, 2006), flow regimes (Stutter et al., 2009), and particle size (Abell and Hamilton, 2013). However, due to these factors, greater quantities of sediment may not necessarily enrich BAP in streamflow or may have no effect (e.g., they may occur in winter when algae are not growing).

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Abbreviations: BAP, bioavailable phosphorus; FRP, filtered reactive phosphorus; PP, particulate phosphorus; SS, suspended sediment; TP, total phosphorus.

Moreover, knowing the source and timing of sediment loss and BAP composition would aid in targeting site-specific strategies to mitigate losses and minimize impact (Marden et al., 2005). Sediment fingerprinting methods can isolate and determine the relative magnitude of sediment sources to streamflow (e.g., Collins et al., 2010, 2013). Occasionally, sediment fingerprinting has been linked to sources of PP loss (Walling et al., 2008), but it has rarely addressed BAP. Given the impact of BAP on water quality, knowledge of where and when BAP is being lost is essential for the optimal placement and timing of mitigation strategies. For instance, McDowell and Wilcock (2004) isolated the source of sediment in a flat agricultural catchment to topsoil. The strategy to mitigate P losses was to decrease topsoil Olsen P concentrations. However, the catchment was flat, with runoff dominated by artificial drainage. If sediment and BAP loss had been found to originate from subsoil, then focusing on decreasing topsoil Olsen P concentrations would have had little effect on P concentration and load in the stream.

The Waituna Lagoon is a large coastal lagoon on the southern coast of New Zealand's South Island and is part of the internationally recognized Awarua Wetland. Inputs of sediment and P into the lagoon have increased over the last 20 yr associated with the development of the surrounding catchment, especially in dairying. Consequently, water quality has declined in recent years to the extent that the lagoon is at risk of having a regime shift from an oligotrophic to a eutrophic state (Robertson et al., 2011). Much of the lower catchment contains Organic soils, which have been identified as a potentially large source of P at the plot scale (McDowell and Monaghan, 2015; Simmonds et al., 2015). However, it is unclear whether or not these soils are the dominant source of P loss at the catchment scale. Furthermore, because the Waituna Lagoon is opened to the sea periodically (and therefore partially flushed), it is important to consider not only total P loads but also the flux of BAP, which may exhibit greater effect in the short term. Hence, the aim of this study was to determine the potential sources of sediment and associated BAP within the streams feeding the Waituna Lagoon, with the secondary aim of recommending the best strategies to mitigate this loss.

Materials and Methods

Study Area

The Waituna Lagoon catchment is located 40 km southeast of Invercargill, Southland, New Zealand. The Lagoon and the immediately surrounding wetland were designated a Ramsar Wetland of International Importance in 1976, with the wider wetland complex being included in 2008. There are three main streams that drain the catchment: Moffat Creek, Carran Creek, and Waituna Creek. Information on land use, land use intensity, and catchment characteristics is given in Table 1. The 30-yr mean annual rainfall and temperature (± SD) are relatively constant over the catchment (1050 ± 100 mm and 9.5 ± 0.2°C, respectively). Annual rainfall and temperature during the study were 1115 mm and 9.6°C, respectively. The use of artificial drainage is common throughout the catchment. This usually consists of 5-cm-diameter "mole" channels ripped 20 cm below the soil surface that lead to tile lines placed 70 to 80 cm below the soil that in turn feed open drains that discharge into each of the streams.

Sampling

Water and sediment sampling sites were located at continuous flow recording stations on each of the three main streams within the catchment (Fig. 1). The Carran Creek and Moffat Creek sites were located approximately 1 and 2.5 km, respectively, from their respective entry points into the lagoon. There are two sampling sites on the Waituna Creek: one in the upper catchment and one in the lower catchment, approximately 18 and 6 km (respectively) from the entry point into the lagoon. Water samples have been taken at all sites on a monthly basis since 2001. However, samples were taken on a fortnightly basis and hourly over a storm event during the study period April 2012 to May 2013.

To trap and collect suspended sediments (hereafter termed "trapped sediment"), six time-integrated samplers based on the design of Phillips et al. (2000) were installed at the Carran Creek and Waituna Creek sites, and four samplers were installed at the smaller Moffat Creek site. These were installed in a V-shape across the stream to steel uprights by rubber ties and at 0.6 times the median water depth to avoid regularly sampling bed load. Samplers collected time-integrated sediment samples for the same period

Table 1. Land use and general characteristics of each catchment.

Characteristic	Waituna Creek		Carran Creek	Moffat Creek
	Upstream	Downstream		
Area, ha	5300	6368†	7223	2271
Land use, % of catchment				
Dairying	57	31	24	62
Drystock	43	40	34	33
Forestry	–	7	1	2
Native	–	22	41	3
Mean stocking rate, stock units ha^{-1}‡	17.6	12.1	9.8	17.0
Dominant two soil orders, % of catchment§	Brown (88), Gley (9)	Organic (66), Podzol (18)	Organic (52), Podzol (30)	Organic (76), Podzol (24)
Flat (<7°) land, %	89	95	99	100
Median flow, m^3 s^{-1}	0.75	0.70	0.12	0.10
75% of maximum flow, m^3 s^{-1}	1.84	1.81	0.27	0.27

† Area only for downstream component of Waituna Creek catchment. Flow is presented for the whole Waituna Creek catchment.

‡ One stock unit refers to one ewe of 55 kg supporting one lamb. A milking dairy cow is about 6.5 stock units.

§ New Zealand soil classification (Hewitt, 1998). Brown, Gley Organic, and Podzols are equivalent to Dystrochrepts, Aquepts, Fibrists, and Aquods, respectively in US Soil taxonomy.

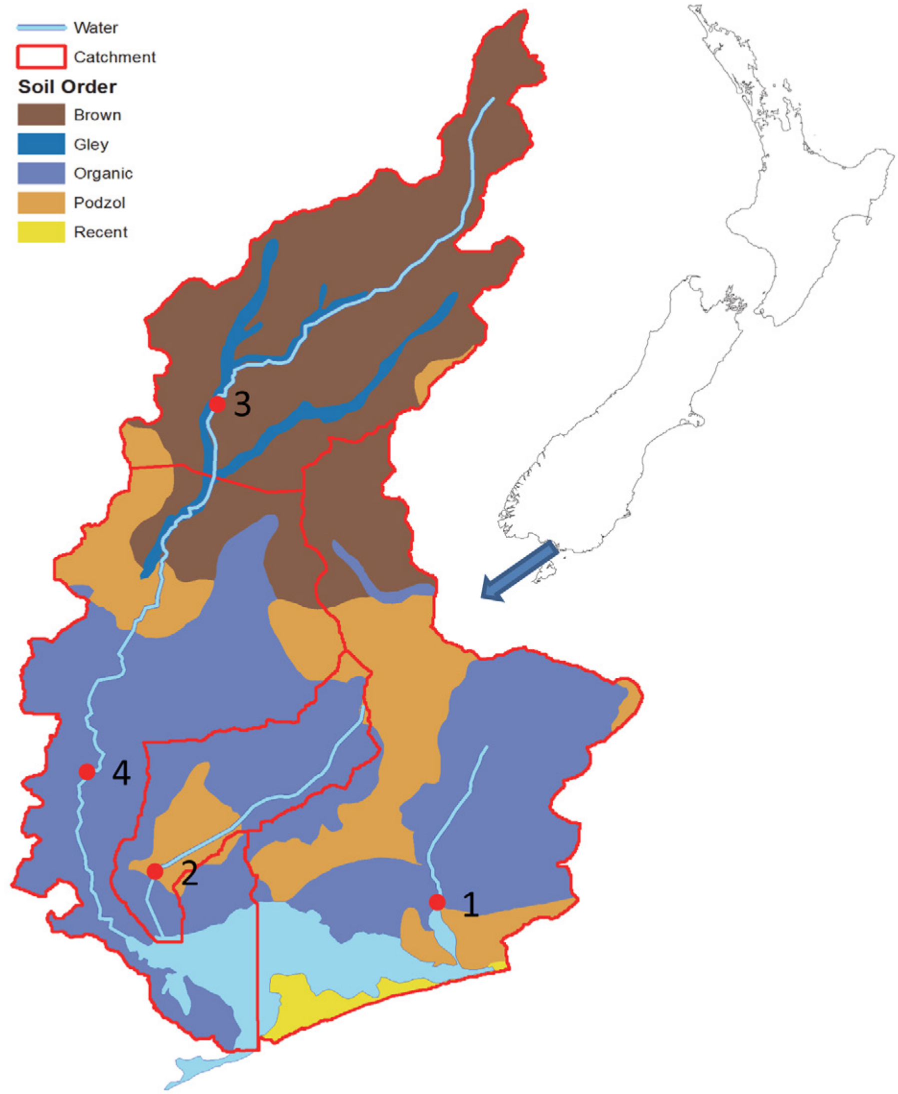

Fig. 1. Location of the (1) Carran Creek, (2) Moffat Creek, (3) Waituna Creek upper, and (4) Waituna Creek lower sampling sites and soil types within the Waituna Lagoon catchment, Southland, New Zealand.

and intervals as water samples. Such samplers have successfully been used for collecting or sampling trapped sediment and associated P in similar sized streams dominated by pastoral agriculture (McDowell and Wilcock, 2004, 2007) but also in streams draining forests (Smith and Owens, 2014), mixed land use (Gruszowski et al., 2003), and arctic desert (McDonald et al., 2010). They capture a time-integrated representative sample of sediments but underestimate the absolute sediment load (Perks et al., 2014).

Trapped sediment samples were not obtained for 2 wk in June and October due to high flows. Hence, data may potentially underrepresent these periods. Sediment mass was determined gravimetrically by weighing a foil dish before and after the drying of a 20-mL sample at 40°C for 6 h. Sediment solutions were subsampled for analysis of BAP, and the remainder of the samples were frozen. Thawing these samples flocculated sediment. Excess water was decanted, and the remaining sediment slurry was placed in a beaker in an oven at 40°C until dry.

The collection of likely sediment source materials occurred in spring 2012 at 20 sites located at 100-m intervals upstream of the sediment samplers. Four replicate samples were taken of the sources: topsoil to 7.5 cm depth, representing the standard depth for pasture production in New Zealand; subsoil from 50 to 57.5 cm deep, commensurate with the B horizon across the catchment; a stream bank (top 2 cm) taken at four points of the top 2 cm of bank sediment every 20 cm down the bank face, beginning from a height equating to 1.5 times median flow; and bed sediment obtained via Ekman dredge of the top 2 cm of bed sediment, representing the depth most likely to interact with the water column. Samples were dried at 40°C, ground, and sieved (<2 mm).

Analysis

Water samples were filtered (<0.45 μm) in the field. In the laboratory, an unfiltered sample was digested (acid persulfate) (Eisenreich et al., 1975) and, together with the filtered sample, was measured for P concentration (detection limit, 0.002 mg P L^{-1}) using the colorimetric molybdenum-blue method (APHA, 1998). This yielded direct measurements of FRP and TP. A subsample of water was also gravimetrically analyzed for suspended sediment (SS). Subsamples (20 mL) of trapped sediment were shaken with a Fe-oxide strip designed to sequester BAP (Method 4) (Bramley and Roe, 1993).

Loads from April 2012 to May 2013 of P fractions and suspended sediment at each site were calculated via the averaging method of Ongley (1973), and the flow duration curve for each site was calculated using daily mean flows from 2008 to 2013. Recent work examining the precision and representativeness of a range of methods indicated that estimates would be the most precise when using an averaging method combined with a flow duration curve that accounts for long-term flow regimes (Snelder et al., 2014).

Before elemental analysis, the particle size distribution was determined on all trapped sediment and source samples. If the distributions of sources and trapped sediment were significantly different, samples were processed to obtain similar particle size distributions. This avoided errors associated with comparing sources that had undergone differing levels of particle size sorting in streamflow before being trapped. Subsamples (30 g) of dried trapped sediment and source samples were mechanically dispersed (Kensington blender) 250 mL of reverse osmosis water for 1 min. The particle size distribution of the resulting slurry was determined using a Malvern Laser particle sizer. A one-way ANOVA on log-mean particle sizes (volume weighted) indicated that bed sediments at the Moffat Creek site were coarser than the other sources and trapped sediment; no differences were found at the other sites. Bed sediment samples from each Moffat Creek site were fractionated to a mean particle size equivalent to that of the trapped sediment (~75 μm). This was achieved by transferring the slurry to a 500-cm^3 cylinder, mixing it, and allowing it to settle before sampling the appropriate depth calculated via Stoke's Law (Rowell, 1994). Fractionation samples were dried at 40°C.

All samples were a analyzed (detection limit, 0.002 $\mu g\ L^{-1}$) for a suite of nutrients as well as trace and rare earth elements (Ca, K, Mg, Na, P, S, Al, Fe, Mn, As, Cd, Cr, Cu, Li, Mo, Ni, Pb, Sr, Zn, Ce, Dy, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Th, Tm, U, and Yb) via inductively coupled plasma–atomic emission spectroscopy after nitric acid–hydrogen peroxide digestion (USEPA, 1997).

Sediment Fingerprinting

Data were analyzed in GenStat (Genstat Committee, 2010) via a two-stage selection process adapted from Collins et al. (2010). The first stage used an ANOVA on ranks to examine the potential for analytes to distinguish between topsoil, subsoil, bank sediment, and bed sediment. This analysis justified the removal of analytes unlikely to contribute to a unique source sediment fingerprint.

The output of the ANOVA on ranks for each analyte across each of the potential sources (Supplemental Tables S1 and S2) showed that significant differences were found for all analytes between sources except for four analytes (Gd, Ho, S, and Th) at the upstream Waituna Creek site, one analyte (S) at the Carran Creek site, and five analytes (As, Cd, S, Sr, and U) at the Moffat Creek site. However, differences were generally driven by the disparity of bed sediments to other sources. Further investigation of the LSD_{05} (back-transformed with bias correction) for each analyte showed that bed sediment was consistently different to other sources at all sites, whereas the two Waituna sites also had a large number of analytes that showed differences between topsoil, subsoil, and bank sediment. We therefore concluded that there was sufficient evidence to separate bed sediments from all other sources across all four sites, and further separation among sources was only possible in the two Waituna Creek sites. However, because few of the analytes were excluded by this first step, we used all of the analytes in the second stage of analysis, except for Na, which was often an order of magnitude greater in bed sediment than in other sources, perhaps due to the occasional intrusion of brackish water (Supplemental Tables S1 and S2).

The second stage of analysis involved a stepwise discriminant analysis on source data (log transformed) to determine the optimum (by minimizing Wilks' lambda) set of elements that separate sources (Collins and Walling, 2002). The results of the discriminant analysis are shown in Table 2. As many as 19 analytes were required to generate the optimum composite fingerprint for the Moffat Creek site, whereas 10 were required for the Waituna upstream and Carran Creek sites.

Once selected, analytes were used in a mixing model to apportion sediment sources to the trapped sediment within each site's catchment. The model for predicted trapped sediment concentrations of each selected element was a linear combination of the four source concentration means, where the coefficients for source types were the same across all elements and constrained to be non-negative but sum to unity. The model was optimized to minimize the residual (lack of fit) for each element as the difference between the log-transformed trapped sediment concentration and the log-transformed modeled concentration. The optimum coefficients are those that minimize the sum of squares of the residuals, subject to the constraints. Because sediment size sorting had already been taken account of, it was not necessary to include a term for this in the model (e.g., Collins et al., 2010).

Confidence intervals for the optimum coefficients were determined using a nonparametric bootstrap method. The log-transformed fitted values and residuals from the optimum model were saved. New bootstrap sink values were obtained by sampling (with replacement) the set of residuals, adding the sampled residuals to the log-fitted values, then back-transforming to get a new bootstrap sample of pseudo-observed values. The model was then optimized for each of the 1000 bootstrap samples generated. The confidence limits for the percentage coming from each source type were obtained from percentiles of the 1000 sets of coefficients obtained from the bootstrap samples.

Table 2. Rank and variety of analytes comprising the optimal composite fingerprints for discriminating between individual sediment sources at each site.

Rank	Waituna Creek		Carran Creek	Moffat Creek
	Upstream	Downstream		
1	Mg	Mg	Mg	Mg
2	P	K	P	Eu
3	K	Ni	K	Ca
4	Al	Zn	Al	P
5	Li	Al	Li	Li
6	Cr	Pb	Cr	U
7	Sr	Li	Sr	Tb
8	Ca	Gd	Ca	Cu
9	S	Eu	S	Al
10	Tb	P	Tb	Sr
11		Dy		Cr
12		As		Gd
13		Ho		S
14		Ca		Yb
15		Sr		K
16		Ce		Pb
17		Pr		
18		Sm		
19		U		

Results and Discussion

Sediment Source Fingerprinting

Mean optimal solutions for the contribution of topsoil, subsoil, stream bank, and stream bed sediment for the two Waituna Creek sites are shown in Table 3. The models for Carran Creek and Moffat Creek could only distinguish between stream bed sediment and all other sources combined (topsoil, subsoil, and stream bank sediment). This may be caused by different soil types. Podzols and Organic soils dominate the Carran and Moffat Creek catchments. These soils have a low anion storage capacity (Hewitt, 1998) and hence a poor ability to preferentially sorb analytes like P and S in topsoil and differentiate them from subsoil.

Data from the Waituna Creek sites show that in general the dominant source of trapped sediment was bank sediment but that the relative contribution from bank sediment was much greater for the downstream site than the upstream site (Fig. 2). Trapped sediment was not collected at the downstream site until August, whereas flow was only collected at the upstream site. In general, the quantity of trapped sediment at each site generally paralleled the frequency and volume of flow generated in preceding storm events (Fig. 3).

The predicted presence of topsoil in the upstream site but not in the downstream site (Table 3) could reflect a number of factors. One is a flashier hydrology with more surface runoff contributing streamflow in headwaters compared with a greater contribution from groundwater at the downstream site (Holden et al., 2004). Other factors likely to contribute to the erosion of topsoil by surface runoff include greater slope; the widespread use of winter- or spring-grazed forage crops (Dennis et al., 2012); and animal treading, leading to soil disturbance, compaction, and increased surface runoff via decreased soil infiltration rates (Curran-Cournane et al., 2011).

Some studies have found that subsoil can contribute substantial quantities of sediment and nutrients to streamflow in catchments that are artificially drained (e.g., Holden, 2006). Tile lines are extensively used within the Waituna Creek catchment and are regularly renovated (i.e., cleaned or relaid) every 10 to 20 yr. However, our data suggested that their contribution compared with other sources was small (Table 3).

At the Waituna Creek downstream site, modeling suggested that bed sediment was a contributing source to trapped sediment

Table 3. Mean optimal solution for the percentage of sediment contributed from each source to sediments trapped at each site.

Source	Waituna		Moffat Creek	Carran Creek
	Upstream	Downstream		
Topsoil				
Spring	28 (9–87)†	0 (0–61)	–‡	–
Summer	40 (0–97)	10 (0–69)	–	–
Autumn	24 (0–92)	1 (0–65)	–	–
Winter	36 (8–84)	1 (0–74)	–	–
Annual	36 (0–82)	1 (0–88)	–	–
Subsoil				
Spring	10 (0–64)	0 (0–70)	–	–
Summer	1 (0–83)	0 (0–80)	–	–
Autumn	0 (0–82)	0 (0–65)	–	–
Winter	0 (0–54)	0 (0–78)	–	–
Annual	0 (0–56)	0 (0–50)	–	–
Bank sediment				
Spring	62 (10–84)	97 (21–94)	–	–
Summer	57 (1–90)	85 (10–100)	–	–
Autumn	76 (4–96)	99 (15–94)	–	–
Winter	64 (10–87)	97 (24–100)	–	–
Annual	64 (14–94)	94 (20–96)	–	–
Bed sediment				
Spring	0 (0–21)	3 (0–56)	1 (0–28)	1 (0–31)
Summer	2 (0–35)	4 (0–61)	0 (0–45)	0 (0–54)
Autumn	0 (0–42)	0 (0–53)	0 (0–76)	0 (0–81)
Winter	0 (0–12)	1 (0–67)	3 (0–25)	1 (0–49)
Annual	0 (0–11)	5 (0–58)	1 (0–35)	1 (0–46)
Topsoil + subsoil + bank sediment				
Spring	–	–	99 (12–100)	98 (12–100)
Summer	–	–	100 (26–100)	100 (4–100)
Autumn	–	–	100 (32–100)	100 (2–100)
Winter	–	–	96 (11–100)	98 (10–100)
Annual	–	–	99 (24–100)	99 (4–100)

† Solutions represent the mean optimal estimate (percentage), with 95% confidence intervals (CIs) in parentheses, determined via bootstrap interrogation of possible solutions. The CIs yield an indication of the fit of the model and the potential range of solutions. An estimate with a narrow range in CIs is more likely, but not exclusively, to be a better fit than an estimate with a wide range of CI.

‡ Sites could not be distinguished from one another.

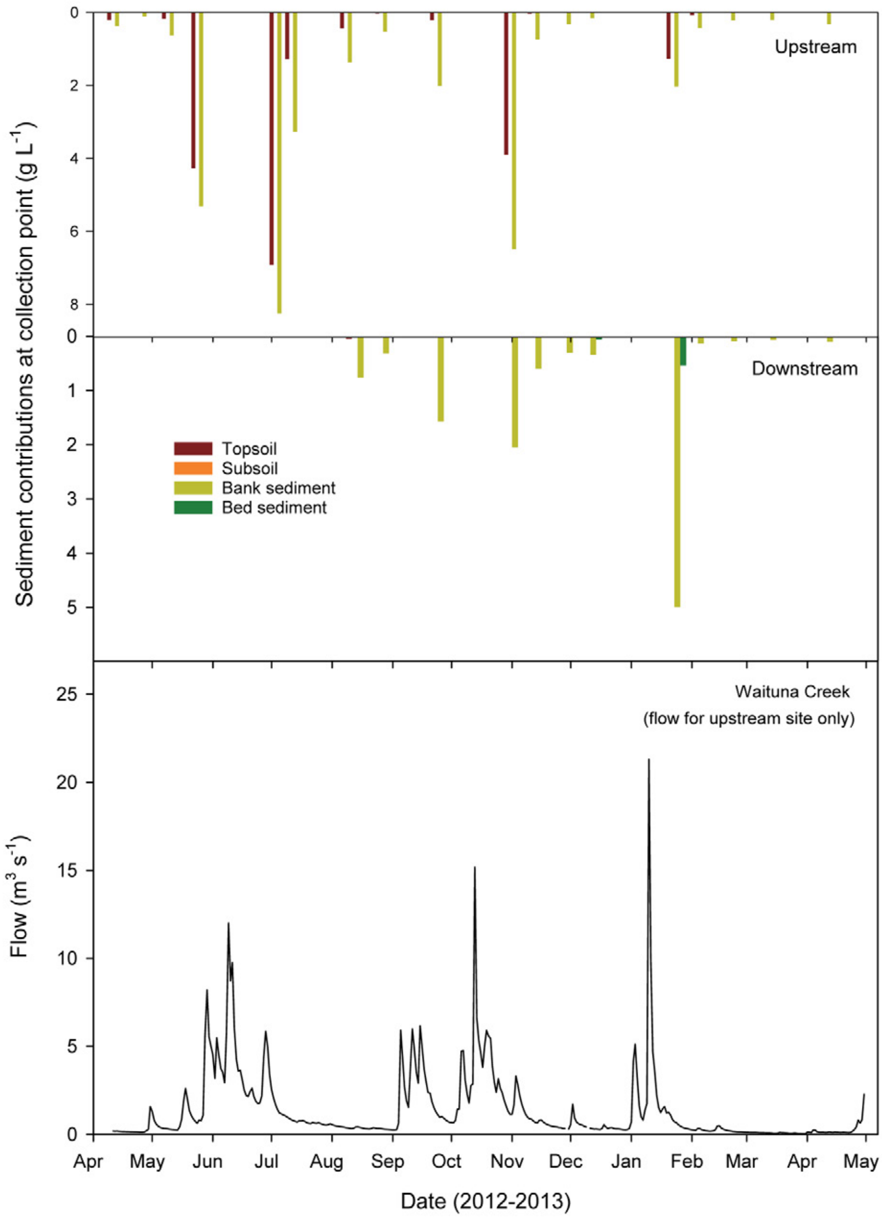

Fig. 2. Mean daily flow and the estimated mean contributions of topsoil, subsoil, bank sediment, and bed sediment to trapped sediment captured at the Waituna Creek upstream and downstream sites.

in January (Fig. 2). Bed sediments contain heavier and coarser particles than usually present in the water column (Stone et al., 2008). Sediment traps were placed at 0.6 times median water depth to avoid continually sampling bedload (Phillips et al., 2000). However, the January sample was taken after the largest storm event recorded during the sampling period (Fig. 2). This large event provided enough energy to remobilize bed sediments into the water column to be trapped in collectors at the downstream site.

The dominant source of trapped sediment in the Waituna Creek catchment was bank sediment. Bank sediments can contribute sediment in streamflow via bank collapse. Major factors that influence bank stability and collapse include steep bank gradient (Budhu and Gobin, 1996), frequent wetting and drying or freeze–thaw cycles (Lawler, 1986; McDowell, 2009), groundwater seepage (Chu-Agor et al., 2009), and changes in bank material erosion or deposition of sediments during streamflow (Fox et al., 2007). However, the dominance of bank erosion as a source of trapped sediment may have been exacerbated by widespread use of open drains in the catchment. In addition to increasing the frequency of possible bank collapse, especially if stock graze near the edge, sediment from open drainage networks may also arise from drain cleaning, which disturbs stream channels and exposes new surfaces to erosion. Ballantine and Hughes (2012) noted that clearing of drains the Waituna Creek catchment in 2012 resulted in SS concentrations 25 times greater than average for the same time of year without clearing (550 vs. 22 Mg). Unfortunately, trapped sediment was not collected at the downstream site until August 2012, but drain clearing may partly explain the high yields of trapped sediment in the upstream site despite lower stormflows than subsequent events (Fig. 2).

Sediment and P Loads

Loads of SS are low on an international and national basis for intensively farmed catchments but reflect the flat topography and low frequency of high-intensity rainfall (McDowell and Wilcock, 2008; Rickson, 2014). Loads of P fractions were moderate compared with other studies of intensively grazed dairying

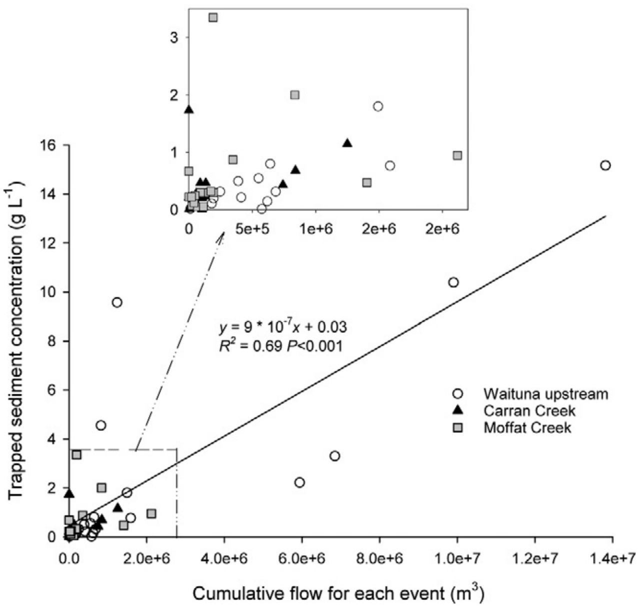

Fig. 3. Relationship between trapped sediment concentration and cumulative flow for each event and each site. The line represents the fit of a linear regression between the two variables across all sites.

in New Zealand (Dymond, 2010; McDowell and Wilcock, 2008). Few studies exist internationally with which to compare these systems (i.e., the majority of research on P losses from dairy farms uses animal housing for some or all of the year). Compared with the Waituna Creek catchment sites, less SS was lost from the Moffat Creek and Carran Creek sites (Table 4). This is partly due to smaller contributing catchments, lower gradients, and differing land use and soil types. Undeveloped peat, which occupies most of the Carran Creek catchment (Fig. 1), is relatively resistant to erosion. However, it can become susceptible to erosion via agricultural development that increases the oxidation of organic matter by cultivation, liming (Grønland et al., 2008; Biasi et al., 2008), and drainage (Holden et al., 2006). Agricultural development near the Moffat Creek site began sooner than in the Carran Creek catchment (Simmonds et al., 2015) and may partly explain why the relative SS catchment yield was greater from Moffat Creek despite it being a smaller catchment.

Similar to SS, TP load was greatest from the Waituna Creek downstream site (Table 4). However, relative TP yield was high for the Carran Creek catchment given that the majority (60%) is undeveloped. Losses were much greater from areas within the catchment that were developed. Recent work has indicated that the Organic soils, which dominate the Carran Creek catchment, are inherently leaky due to low anion storage capacity, resulting in poor soil P sorption. In an 18-mo study, McDowell and Monaghan (2015) measured 65 kg P ha^{-1} lost in subsurface flow from an Organic soil in the Waituna Lagoon catchment with <2% anion storage capacity. A nearby soil, deemed to represent an intergrade between an Organic and Podzol soil, had a slightly greater anion storage capacity (to 10%) and much less subsurface flow P lost (4 kg P ha^{-1}). Small areas of Organic soils are also present and used for agriculture in the Moffat Creek catchment. Greater relative yields, especially of FRP, would suggest that these areas contribute significant amounts of P to streamflow.

Bioavailability of P Losses

Data for BAP extracted from trapped sediment are given in Table 5 and Fig. 4. Estimates of BAP were much greater relative to trapped sediment for the Carran and Moffat Creek sites compared with the Waituna Creek sites (Fig. 4). This can be attributed to the low P sorption capacity (low anion storage capacity) and bulk density of Organic and Podzol soils, meaning that, compared with the mineral Brown soils, eroded (and trapped) sediment in Carran and Moffat Creeks will likely contain more loosely bound (bioavailable) P per unit mass. In general, trapped sediment loads mirrored the size of preceding stormflows (Fig. 2). However, the linear relationship between BAP concentration and trapped sediment for Carran and Moffat Creeks (Fig. 4) suggests that a consistent source is being eroded or that there

Table 4. Catchment yield and loads of filtered reactive P, total P, and suspended sediment at each site in the Waituna Lagoon catchment from April 2012 to May 2013.

Site	Filtered reactive P		Total P		Suspended sediment	
	Catchment yield	Load	Catchment yield	Load	Catchment yield	Load
	kg ha^{-1}	kg	kg ha^{-1}	kg	kg ha^{-1}	Mg
Carran Creek	0.11	811	0.29	2217	24	188
Moffat Creek	0.28	634	0.60	1372	30	67
Upper Waituna Creek	0.02	117	0.17	921	59	317
Lower Waituna Creek	0.05	622	0.41	4834	139	1625

Table 5. Mean ratio (×1000) of bioavailable P to trapped sediment captured at each site by season.

Season	Upper Waituna Creek	Lower Waituna Creek	Moffat Creek	Carran Creek	All sites
Spring	0.33 (24)†	0.26 (29)	0.42 (45)	0.62 (44)	0.42
Summer	0.65 (13)	0.61 (43)	0.70 (20)	1.00 (12)	0.75
Autumn	0.87 (15)	0.54 (10)	2.18 (19)	1.58 (13)	1.26
Winter	0.58 (48)	0.13 (18)	0.62 (15)	0.72 (31)	0.50
Annual	0.61	0.39	1.00	1.02	
$LSD_{\text{Site ignoring season}}$ = 0.33‡					
$LSD_{\text{Season ignoring site}}$ = 0.32					
$LSD_{\text{Site by season}}$ = 0.65					

† The seasonal proportion of total sediment captured at each site is given in parentheses.

‡ The LSD is given for the comparison of mean ratios for all sites (ignoring seasons), seasons (ignoring sites), or the interaction of site and season.

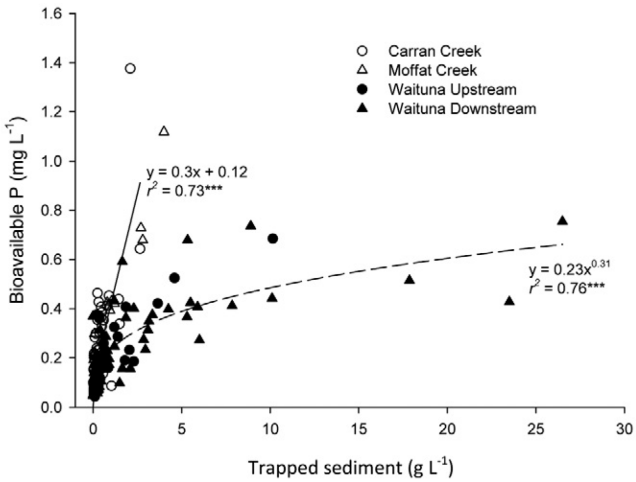

Fig. 4. Relationship between bioavailable P and trapped sediment captured at each site. Regression equations are for the fit of combined data for Carran and Moffat Creeks, separate from data combined from the upstream and downstream sites in the Waituna Creek. ***Significant at the $P < 0.001$ level.

was little particle size sorting. In contrast, BAP concentration tended to decrease and form a curvilinear relationship, relative to trapped sediment measured in the Waituna Creek sites. The most likely explanation is a change in particle size, especially an increase in coarse-sized, low-P particles at higher flows (Ellison and Brett, 2006; Grundtner et al., 2014). In contrast, the high organic matter and low mineral content of the Organic and Podzol soils would result in eroded material of consistent particle size. This is further supported by sediment fingerprinting data, which suggested only a minor contribution of P-enriched sources such as topsoil (which receives regular inputs of P via fertilizer and dung) in trapped sediment for all but the Waituna Creek upstream site (Table 3).

Not only were there significant differences in the enrichment of BAP relative to trapped sediment between sites, but summer and autumn BAP concentrations were generally greater than spring and winter samples (Table 5). Abell and Hamilton (2013) found that nearly all the PP sampled from an autumn event into Lake Rotorua, New Zealand was bioavailable when measured via an algal bioassay. In contrast, only 25% was potentially available in a sample taken during winter. The difference was largely attributed to the large winter event transporting coarse sediment containing little P in largely refractory forms.

Fertilizers, dung, denuded pasture, and soil are all potential sources of BAP loss from grazed pastures (McDowell et al., 2007). Of the land uses present in the Waituna Lagoon catchment, dairying is likely to lose more BAP than either native or drystock land uses (McDowell and Wilcock, 2008). Past work has shown that more BAP originates from erosion and bank disturbance during winter and spring (McDowell and Wilcock, 2007), whereas practices such as the application of P fertilizers can enrich BAP in summer and autumn, especially where the soil has little capacity to retain it (McDowell and Monaghan, 2015). The greater enrichment of BAP relative to total P in the Moffat and Carran Creek catchments compared with the Waituna Creek catchment indicates that P losses are being transported to the lagoon without much in-stream attenuation. Therefore, to minimize the impact in the lagoon, the quantity, timing, and form of P will have to be considered in management.

Management

There are a range of farm-scale strategies available to minimize the erosion and loss of topsoil and associated BAP into streamflow from catchments dominated by grazed pasture (Table 6). These strategies have a range of cost (including labor requirements) and effectiveness. It is recommended that to avoid impairing farm profitability, strategies should be implemented in the order of most cost-effective first (McDowell, 2014). However, if greater or quicker decreases are required, then strategies may be implemented in a different order.

Site-specific targeting strategies to the correct source of sediment and BAP loss will increase effectiveness and cost-effectiveness if prioritized. Across all sites, bank sediment was an important source (Table 3). However, bank material could not be distinguished from topsoil or subsoil in the Moffat and Carran Creek sites. Therefore, "bank sediment" could represent sediment that has eroded from topsoil and settled on stream banks rather than "true" bank material. Hence, in addition to strategies that promote bank stabilization (e.g., fencing and riparian planting), a safe approach would include strategies to prevent topsoil erosion (e.g., not pugging [viz. poaching] soil by overgrazing wet pastures and minimizing the use of winter forage crops), especially at the Waituna Creek upstream site where contributions from topsoil were more likely.

Mitigation strategies should also consider when losses occur because the catchments feed into a lagoon, which normally would place the focus on decreasing total P loads. However, the Waituna Lagoon is opened every few years and flushed. This reduces the residence time but increases the effect of BAP in the short term, especially in summer and autumn when algae are growing fastest. Table 6 gives a qualitative estimate of the relative effectiveness of different strategies aimed at mitigating BAP loss from different soils in the Waituna Lagoon catchments in summer-autumn and winter-spring. This may further help focus some strategies, such as reducing P inputs (e.g., effluent) to Organic soils likely to lose much BAP in summer-autumn compared with grass buffer strips and fencing that promotes bank stabilization and amends topsoil losses in winter-spring.

Off-farm strategies may also mitigate the delivery of sediment and BAP to a lagoon by focusing on the drainage network. Dredging sediments from open drains can decrease BAP flux by oxidizing reduced sediments (improving P sorption), sequestering P in recolonizing biofilms, and stabilizing the bed via macrophyte growth (Smith and Huang, 2010). The efficiency of dredging would be improved by starting from the top of the catchment, allowing any temporary increases in sediment (Ballantine and Hughes, 2012) to be trapped by downstream vegetation before it too is cleared. Controlled drainage structures, designed to raise the water table and enhance denitrification and sedimentation of particles and BAP (Tan and Zhang, 2011), may not be ideal due to the wet-cool conditions. However, peak runoff control structures that contain culverts at specific depths to attenuate runoff and allow for sediment and P to settle out and denitrification to occur (Marttila and Kløve, 2010) could be easily implemented within the existing open drain network.

Table 6. Summary of the ranked (into quartiles) range of cost and effectiveness of farm-scale strategies to mitigate bioavailable P and total P from average dairy, deer, and all farms in New Zealand (modified from McDowell [2014]) and the relative mitigation effect on bioavailable P relative to total P.

Mitigation strategy	Suitable land use	Cost†	BAP mitigation effectiveness‡	TP mitigation effectiveness‡	Mitigation effectiveness ratio (BAP/TP)	Seasons where mitigation of BAP is likely greatest§	Soil order where BAP mitigation is likely greatest§
			%				
Low rate effluent application to land	dairy	low	very high	high	0.82	summer-autumn	Organic
Stream fencing	all	low	high	medium	0.58	winter-spring	Brown
Greater effluent pond storage	dairy	low	medium	high	1.20	summer-autumn	Organic
Optimum soil test P	all	low	medium	high	1.51	summer-autumn	Organic
Low solubility P fertilizer	all	low	low	medium	1.70	summer-autumn	Brown
Alternative wallowing	deer	medium	very high	very high	0.90	summer-autumn	Organic
Widening flood irrigation bays	all	medium	very high	very high	1.00	NA¶	NA
Dams and water recycling	all	medium	very high	very high	0.99	NA	NA
Tile drain amendments	all	medium	high	high	1.01	summer-autumn	Organic
Grass buffer strips	all	medium	medium	medium	0.84	winter-spring	Brown
Red Mud (bauxite)	all	high	very high	very high	1.58	summer-autumn	Organic
Restricted grazing of cropland	all	high	high	medium	0.62	winter-spring	Organic
Alum to cropland	all	high	medium	medium	1.33	summer-autumn	Brown
Preventing fence-line pacing	deer	high	low	low	0.11	winter-spring	Brown
Alum to pasture	all	high	low	low	8.67	summer-autumn	Organic
Sorbents in and near streams	all	very high	high	very high	1.10	summer-autumn	Organic
Constructed wetlands	all	very high	medium	low	0.29	winter-spring	Brown
Natural seepage wetlands	all	very high	low	low	0.06	winter-spring	Brown
Sediment traps	all	very high	low	low	0.67	winter-spring	Brown

† Cost categories: low, from net profit to a cost of <\$35 kg^{-1} P mitigated; medium, \$36 and \$110 kg^{-1} P mitigated; high, \$111 and \$205 kg^{-1} P mitigated; very high, >\$205 kg^{-1} P mitigated.

‡ Filtered reactive P (FRP) is used here as an analog of bioavailable P (BAP). Categories refer to median % effectiveness categorized for FRP: low, <29%; medium, 29–37%; high, 37.1–60%; very high, >60%. For total P (TP), categories are: low, <24%; medium, 24–43%; high, 43.1–60%; very high, >60%.

§ Targeted estimates are given of seasons where mitigation of BAP would likely be greatest and appropriate for either the Brown soils in the upper and lower Waituna Creek catchments or for the Organic (including Podzol and Gley) soils in the Carran Creek and Moffat Creek catchments.

¶ Not applicable to the Waituna Lagoon catchment.

When applied to sediment fingerprinting data, strategies should focus on minimizing stream bank erosion as the major source of BAP and sediment throughout the catchment. However, when considering losses in space and time, the Waituna Creek catchment data suggested that strategies should also minimize contributions from topsoil in the winter-spring period, whereas in the Carran and Moffat Creeks strategies should reduce P inputs (e.g., effluent) to Organic soils likely to lose much BAP in summer-autumn when the impact on the Waituna Lagoon is quickest. This study highlighted the need to identify sources and timings of BAP and sediment loss to surface water before recommending mitigation practices, which without this information may be slow or not succeed.

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