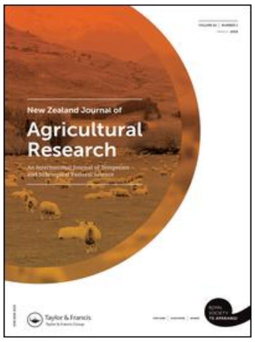

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Quantifying contaminant losses to water from pastoral landuses in New Zealand II. The effects of some farm mitigation actions over the past two decades

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ABSTRACT
In New Zealand the primary sector together with central and local government agencies have been promoting measures to mitigate the adverse effect of farming practices on water quality over the last few decades. We assessed the effectiveness of some key measures such as stock exclusion, riparian protection, and nutrient and effluent management on reducing losses of nitrogen (N), phosphorus (P) and sediment to water. Our aim was to determine how much progress has been made in decreasing contaminant discharges between 1995 and 2015 and to determine what the loads would have been if no mitigation had occurred. To do this we estimated losses from 37 dairy and non-dairy/sheep/beef farm typologies that captured the main attributes of production and contaminant loss pathways, nationally. We also accounted for the rate of uptake of measures. Our findings indicated that while the implementation of these measures has helped to reduce P losses (an estimated 20%–25% reduction) to water, they have not been sufficient to off-set estimated increases in N losses (25%) due to expansion of dairy land over the same period. National sediment load is estimated to have decreased (29%) because of afforestation and other soil conservation works.

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Introduction

In response to growing community concern about the effects of increasing land use pressures on water quality in New Zealand, considerable investment has been made by government and land owners to identify and implement affordable land management practices, hereafter termed measures, that can mitigate the impacts of farming activities on water quality. Overviews of these measures are summarised elsewhere (e.g. Houlbrooke et al. 2004a; Monaghan et al. 2007; Basher 2013; McKergow

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et al. 2016; DairyNZ 2019). Many have now become widely accepted as expected attributes of modern farming systems and focus on reducing losses of pollutants such as nitrogen (N), phosphorus (P), sediment and faecal microorganisms (FMOs, indicated by the proxy *Escherichia coli*). They include riparian protection, improved management of nutrients imported onto farms (esp. fertiliser), more careful scheduling and application of effluents and irrigation water and tree planting on erodible hill country. However, their level of implementation has varied depending on geography and catchment characteristics, affordability and the perceived efficacy of a particular measure on reducing one or multiple water contaminants (Granger et al. 2010).

Knowledge of what measures have been applied, and their likely effectiveness, is helpful for prioritising future policy decisions and extension efforts that seek to improve water quality outcomes. The aim of this paper was therefore to estimate the impact of some widely accepted farming mitigation measures on load generation against a backdrop of land use change and farm intensification (PCE 2004). This analysis infers how bad (or better) water quality could be without such actions. The approach taken was to compare modelled discharges from pastoral farms of N, P and sediment for 1995 and 2015 and isolate the specific effects of key management interventions that have been widely promoted amongst farmers and rural professionals between these dates. Spatial estimates of the extent of different types of pastoral farming for these dates were factored into calculations to ensure that assessments considered the likely important effects of the encroachment of intensive land use practices onto land that has traditionally been deemed less suitable for such intensive activity. Assessments of the degree of implementation of specific measures were also factored into calculations. An accompanying paper by McDowell et al. (2020) considers the maximum load of contaminants that could be mitigated for scenarios that assumed (i) all of the established mitigation measures considered here were implemented, where suitable, by 2015, and (ii) all established and developing (i.e. those not in common use) measures were implemented by 2035.

Our analysis would, ideally, include a quantitative consideration of reductions in faecal transfers from land to water due to the implementation of the mitigation measures documented above. Based on our present state of knowledge about *E. coli* cycling and transfers from soil to water, and the limitations of modelling tools that are currently available, such assessments carry a considerable degree of uncertainty. For example, a recent literature review of international data that document the effectiveness of stream fencing for reducing *E. coli* concentrations identified studies where effectiveness ranged from 0% to 97% (Muirhead 2017). Consideration of base-flow and storm-flow stream conditions (Muirhead 2015) and the existence of four different numeric metrics that exist for defining 'swimability' (MfE 2017) are factors that further complicate any analysis and interpretation of mitigation effectiveness. Because of this complexity and *in lieu* of a detailed modelling approach, assessments of faecal pollution mitigation reported here are confined to summary narratives of the limited body of research that we could find in the literature. A wider discussion of the current modelling approaches for assessing faecal contamination can be found in the supplementary information.

Materials and methods

Approach

Assessments of mitigation effectiveness for reducing N, P and sediment losses were undertaken separately for dairy and non-dairy (sheep, beef) pastoral land-uses. A typology-based approach was used to derive estimates of N & P losses, as described by Monaghan et al. (2021); only a brief overview is provided in the following. We did not pursue an empirical approach comparing water quality at specific sites in 1995 and 2015 owing to inconsistencies in the data such as poor spatial or temporal coverage or sites beginning or ending their recording during this period (Larned et al. 2020). For dairy farmland, primary consideration was given to the inherent vulnerability of contaminant loss from the farmed landscapes, recognising how factors such as soil type, slope and rainfall strongly influence the transfers of N, P and FMOs from land to water. The approach for non-dairy pastoral land instead considered the productive potential of the varied farmed landscapes (as mainly governed by slope, temperature and rainfall factors) as a primary consideration, in recognition of the driving influence that production potential exerts on farm N loss risk. Nutrient budgets for each farm typology were prepared using the Overseer® Nutrient Budgeting software version 6.3.1 (Wheeler et al. 2008, 2011; Cichota et al. 2012), hereafter referred to as *Overseer.* Forty farm models were constructed for dairy farmland (20 most abundant typologies×2 periods) and 34 farm models for non-dairy land (17 typologies×2 periods). Because sediment modelling requires a fundamentally different modelling approach to that for estimating N and P losses due to the underlying pattern of natural variation in erosion rates not controlled by land use, the New Zealand Empirical Erosion Model (NZeem®) was used to assess the effectiveness of measures that have been implemented for controlling sediment losses.

Modelling the effectiveness of mitigation measures for reducing N and P losses to water

We analysed established mitigation and management practices that we consider have (i) been broadly accepted as good management practices (e.g. https://www.dairynz.co.nz/environment/ and https://beeflambnz.com/compliance/environment), or (ii) been implemented to some degree by the farming community. These measures are documented in Table 1 and have been categorised into five main strategies: riparian protection, land retirement, the improved management (correct application rates, methods and timings) of fertiliser, irrigation water and farm dairy effluent, and off-paddock grazing management. The latter two strategies are of most relevance to dairy farms and our analysis of these measures is therefore confined to this farm type only. A companion paper (McDowell et al. 2020) will focus on the potential of the full implementation of established and other, developing, measures that could in the future further mitigate farming's impacts on water quality.

The protection of riparian margins by fencing is now widely recognised as a priority consideration for livestock farming systems due to the beneficial effects it has on stream bed and bank stability and the prevention of direct deposition of animal excreta into or near water (McKergow et al. 2016). Planting these margins will also provide shading and increase biodiversity. While a high level of stream fencing is now reported for dairy farms

Table 1. Mitigation measures selected for modelling assessments of effectiveness for reducing farm-scale losses of N and P to water from dairy and sheep-beef farms.

Management strategy	Mitigation measure	Alignment to typology structure	Assumed implementation 1995[1]	Assumed implementation 2015[2]	References for assumed implementation
Dairy farms					
Riparian protection	Stream fencing to exclude stock	All	48%	97%	DairyNZ 2017
Fertiliser management	Reduced surplus soil P fertility	All			Ballance AgriNutrients soil test records
	Use of low solubility forms of fertiliser P	Farms on Poorly drained soils or slopes > 7°	0%	6%	DairyNZ 2016
	Judicious scheduling of N and P fertiliser applications to avoid risk months	All	P = 100% N = 74%	P = 77% N = 43%	DairyNZ 2016
	Reducing excessive inputs of fertiliser N	All	96%	63%	Butler and Johnston 1997; DairyNZ 2016
Effluent management	Land application of FDE	All	35%	97%	Longhurst et al. 1999; Wilcock et al. 1999; DairyNZ 2016
	Enlarged areas receiving FDE	All	0%	24%	DairyNZ 2016
	Targeted fertiliser returns to effluent-treated areas	All	0%	41%	LIC 1996; DairyNZ 2016
	Deferred and/or low rate effluent irrigation	Poorly drained soils; farms on moderate slopes	0%	11%	DairyNZ 2016
Off-paddock management	Wintering in a barn or on a standoff	All	0%	7%	DairyNZ 2016
Irrigation management	Reduced flood irrigation by-wash	Irrigated farms	0%	47%	Section 5.4.4 from PCE 2004; DairyNZ 2016
	Reduced over-watering	"	<10%	39%	Section 5.4.4 from PCE 2004; DairyNZ 2016
Sheep-beef farms					
Riparian protection	Stream fencing to exclude stock	All	25%	35%	Brown 2017
Fertiliser management	Reduced surplus soil P fertility	All	41%	52%	Ballance Agri-Nutrients soil test records
	Judicious scheduling of N and P fertiliser applications to avoid risk months	All	P = 20%, N = 20%	P = 31%, N = 31%	Brown 2017
Land retirement	Stock exclusion and/or planting trees	All	By farm type	By farm type	BLNZ data; Horizons Regional Council data.

[1]based on references cited, expert assessments by Dairy and Fertiliser Industry stakeholders and Regional Council records (where available).
[2]based on Clean Streams Accord reporting (DairyNZ 2017) or Dairybase farm file information (DairyNZ 2016).

(Table 1), it is somewhat lower for sheep-beef farms, reflecting the greater fencing cost and reduced affordability of this measure for most sheep-beef farming systems. Practices to improve the efficiency of nutrient use in pastoral agriculture are now also widely recognised and accepted as part of modern farming activities (Monaghan et al. 2007). These represent a suite of measures that include established protocols for assessing soil nutrient status; identifying target soil test ranges to avoid situations of surplus or deficit; fertilisation to ensure balanced pasture nutrition is achieved; pasture analysis to diagnose the adequacy of fertilisation practices; nutrient budgeting as a decision support tool; and consideration of fertiliser form and application timing to minimise the risk of incidental losses of fertiliser N and P. These measures are particularly relevant to dairy farms where farm inputs of fertiliser and feed are usually relatively large, corresponding with their higher farming intensities and product outputs.

The third key area experiencing considerable research and extension effort is the improved management of farm dairy effluent (FDE). From 1995 onwards, the two-pond treatment system, with discharge to a stream, began to be phased out because it was recognised that the nutrient-rich aerobic pond discharge had adverse environmental impacts on surface water quality (Hickey et al. 1989; Wilcock et al. 1999). Although irrigation to land of raw FDE is now a required treatment option for most regional councils, adherence to nutrient and hydraulic loading guidelines is required for some soil types to ensure that FDE irrigation events do not exceed the soil's infiltration or water holding capacities. This is particularly important for mole and pipe-drained soils or soils with impeded drainage where the risk of raw or partially treated FDE discharges during or immediately following effluent irrigation is high (Houlbrooke et al. 2008). These discharges can represent a relatively large proportion of the P and FMOs transferred to waters (Houlbrooke et al. 2004a; Monaghan et al. 2010). Deferred, low rate and/or low depth FDE application methods can minimise such risk and have been widely adopted on farms with some of these soil risk attributes (Houlbrooke et al. 2004b; Laurenson et al. 2017) (Table 1).

Of note in Table 1 is the inclusion of off-paddock wintering of dairy cattle, such as the use of barns and standoff pads, which has the potential to reduce N leaching (Cardenas et al. 2011; Christensen et al. 2012) (and probably losses of P, sediment and FMOs). Although questions remain about the feasibility and wider applicability of this general strategy due to issues around cost and perception, it is included here because surveys have shown that it has been implemented on some, albeit relatively few, New Zealand dairy farms. Improved water irrigation practice is the remaining measure evaluated, focussing on (i) the removal of flood irrigation and (ii) reduced over-watering. Although irrigation is not a widespread land-use practice nationally, it is particularly important for the Canterbury region and can potentially have an important role in transferring nutrients and faecal material from land to water (Monaghan et al. 2009). Irrigation management settings for the Base farm files of each irrigated typology were chosen based on the most common management in that typology. For example, the irrigated farms on Light soils had 54% of farms with a 'managed irrigation application' setting; the *Overseer* file was therefore constructed to reflect this. In contrast, the Base farm on the Well-drained irrigated typology was constructed assuming a fixed irrigation return period, as most farmers in this typology (>60%) did not have a managed application.

The effectiveness of each of the mitigation measures documented in Table 1 was assessed by manipulating relevant management settings in the *Overseer* file for each of the constructed typology farms (20 in total for dairy and 17 for sheep-beef farms). For each mitigation x typology scenario, a potential loss reduction was calculated as the difference between farm scale estimates of N (or P) loss, assuming that mitigation implementation was nil or 100%. An actual mitigated loss was then estimated for dairy farms by multiplying this potential loss with a % implementation value that was derived from the Dairybase farm records (DairyNZ 2016) or from the other sources referred to in Monaghan et al. (2021). This step was undertaken for each of the farm typologies that were considered, for 1995 and 2015. As an example, if off-paddock grazing management was estimated to potentially reduce farm-scale losses of N from 50 (nil implementation) to 40 kg N $ha^{-1}yr^{-1}$ (100% implemented), the potential loss reduction equals 10 kg N $ha^{-1}yr^{-1}$; assuming this is implemented on only 10% of farms in a particular typology, the actual mitigated loss is 1 kg N $ha^{-1}yr^{-1}$. The purpose of calculating both potential and actual loss reductions was to (i) identify which measures deliver the largest loss reductions, and (ii) quantify how much mitigation could still be achieved if implementation was assumed to increase to 100%. The analysis presented here is confined to estimates of actual mitigation effects, however; estimates of potential effects are presented in the companion paper of McDowell et al. (2020). Dairybase file information was used to calculate many of the implementation settings assumed for the dairy farm scenarios constructed for 2015. Exceptions to this were for stream fencing, where a uniform implementation of 97% was assumed (Table 1), and the soil P test information used for assessments of P runoff risk for mitigated v. un-mitigated scenarios.

Fewer mitigation options are available for sheep and beef relative to dairy (Table 1). Riparian protection is included because sheep and beef farming dominate New Zealand pastoral land use (Stats NZ 2018) and are likely to encompass a high proportion of waterways relative to other land uses. Mitigations involving improved fertiliser management are also relevant, as significant quantities of fertiliser nutrients are annually applied to support higher levels of sheep and beef farm production (PCE 2004). Land retirement is also recognised as an important measure for improving water quality outcomes where contaminant loads can be reduced through stock exclusion and cessation of nutrient inputs via fertiliser. Several large national programmes currently promote and incentivise land retirement from pastoral use (e.g. LINZ 2018; QEII 2018; MPI 2018a; MPI 2018b). We draw on data from the Survey of Rural Decision Makers (SRDM), (Brown 2017) to estimate the 2015 percent implementation rates for sheep and beef riparian protection and judicious scheduling of N and P. This is a biennial national survey targeting all farming types, with a response of 4000 survey participants for the 2017 year. Results from the 2017 survey involved questions more closely aligned to the mitigations examined in this paper (cf. 2015 survey). No questions were directly related to the timing of P-fertiliser, so we assume the same implementation percentage for N-loss fertiliser (31%). Reduced surplus soil P fertility implementation rates are estimated by backward linear extrapolation of soil test records. Land retirement from grazing was calculated as the difference between total and effective area reported by Beef and Lamb NZ (2018). The potential area for land retirement in hill country was estimated using land-retirement type environmental assessments of 420 hill country farms in the Horizons Region (Mitchell and Cooper 2006; Manderson et al. 2013), while non-hill country is estimated as the additional proportion of farm land that could be retired and planted for riparian protection according to the intersection of River Environment Classification (Snelder et al. 2005) higher order streams with grassland covers (Land Cover Database version 4 (LCDB-4), http://maps.scinfo.org.nz/index.html) within the sheep and beef farming extent. We estimate the potential for further realistic retirement from grazing for environmental purposes at 11% for hill country farms and 2% for other farm types. All other implementation rates are based on expert assessments by industry sources (Table 1).

Assessments of sediment mitigation

Assessing the effect of sediment mitigation requires data on variation in erosion rates, how much mitigation has been implemented and where, and how effective mitigation is in reducing sediment loads. In New Zealand, mitigation is dominated by the (i) treatment of hill-slope erosion (landslides, gullies, earthflows) using soil conservation works implemented as part of Whole Farm Plans (WFPs), typically spaced-tree planting, afforestation, or land retirement and reversion, and (ii) treatment of bank erosion by retirement of riparian areas through fencing and/or planting (Basher 2013). The effect of these two components is evaluated separately here.

As described in Monaghan et al. (2021) land cover maps in 1996 and 2012 were nominally used to represent covers for 1995 and 2015, with the difference effectively representing the effect of changes in woody vegetation cover (forest and scrub) extent but does not account for erosion mitigation by space-planted trees. To establish how much erosion mitigation has been implemented and where, information was sought from regional councils which are responsible for managing most erosion mitigation in New Zealand. They provided spatially referenced (GIS) data that was variable in quantity and quality but represented the best available coverage of the extent of erosion mitigation, the type of mitigation implemented, and the date that it was implemented. Because there is a long history of soil conservation, the date of implementation was used to identify pre- and post-1995 erosion mitigation, and to factor in the maturity of trees since they are not fully effective in reducing erosion until they have reached maturity. Data on the implementation of riparian retirement from grazing was also derived from the Survey of Rural Decision Makers which provides a regionally-based estimate of the extent of implementation of riparian exclusion. No data was available on the extent of riparian fencing/planting prior to 1995 so we assumed all the riparian mitigation was installed post-1995. Similarly, regional councils in the South Island were not able to provide an estimate of the area covered by WFPs in either 1995 and 2015, so analysis for the South Island only incorporates the effect of vegetation change (woody to non-woody or vice versa) and riparian exclusion.

Evaluating the effectiveness of WFPs and riparian fencing/planting used approaches that accounted for the effectiveness of different mitigation practices and the time for those mitigation practices to be fully effective, as described in Dymond (2010; Dymond et al. 2016a). A fully implemented WFP was assumed to reduce hillslope erosion by 70% (Hawley and Dymond 1988; Hicks 1992; Thompson and Luckman 1993; Douglas et al. 2009, 2013; McIvor et al. 2015) while afforestation was assumed to reduce hillslope erosion by 90% (Phillips et al. 1990; Hicks 1992; Marden and Rowan 1993; Fransen and Brownlie 1995); riparian retirement was assumed to reduce bank erosion by 80% (McKergow et al. 2007, 2016; Hughes 2015; Dymond et al. 2016a). All farms where WFPs had been implemented were selected from the GIS data provided by regional councils. This provided a national dataset of farm boundaries where WFPs had been implemented and an associated date of implementation. The farms were then split into pre-1995 or post-1995 periods (to 2015), based on the date of implementation of the WFP. Because space-planted trees take time to be fully effective, a maturity factor was calculated for each period based on a time of 15 years for full maturity of space-planted trees (Dymond et al. 2016a). All farm plans implemented prior to 1980 and 2000 were therefore deemed to be fully mature for the respective periods (pre- and post-1995). For the remaining years (1981–95, 2001–2015) a linear relationship between age and effectiveness was assumed and applied to incorporate the maturity of trees.

NZeem® does not distinguish the processes contributing to erosion. NZeem® data was therefore partitioned into hillslope and bank erosion components. The 70% effectiveness for fully implemented WFPs was applied to the hillslope erosion component of the sediment budget only. To determine the proportional contribution of hillslope erosion and riverbank erosion, we used the sediment budget model SedNetNZ (see Dymond et al. 2016a) which does account for contributing erosion processes. It is available for several regions of New Zealand (Hawke's Bay, Waikato, Northland, Manawatu-Whanganui) and was used to estimate the average contribution of bank and hillslope erosion to sediment budgets. The results showed that the average contribution of bank erosion across these regions amounted to 18%, with 82% from hillslope erosion processes. Therefore, 82% of the NZeem®-estimated erosion rate was reduced by 70% within the boundaries of the farms with completed WFPs and multiplied by the maturity factor for the farm.

As noted above, stock exclusion and riparian retirement were assumed to reduce bank erosion by 80%. The results of the SRDM (Brown 2017) were used to derive the percentage of farms with riparian retirement implemented to restrict stock access to major streams; 18% of the NZeem®-estimated erosion rate was reduced by 80% within the area containing major streams (>1 m wide, >30 cm deep, and permanently flowing). We assumed all the riparian retirement had been implemented post-1995. Table 2 summarises the riparian fencing and WFP data by region. This methodology resulted in the following equation to calculate the effect of hillslope erosion mitigation and riparian retirement for the NZeem®-derived estimates of erosion rate in 1995 and 2015:

$$ER = NZeem - ((NZeem \times 0.82 \times 0.7 \times M_f) + (NZeem \times 0.18 \times 0.8 \times F_{rf}))$$

where ER is the erosion rate (t km^{-2} yr^{-1}), $NZeem$ is the erosion rate estimated for 1995 or 2000 (t km^{-2} yr^{-1}), M_f is the maturity factor of the WFP, and F_{rf} is the regional fencing factor as the proportion of major streams fenced based on the SRDM. The analysis was first carried out for 1995, reducing the NZeem®-derived erosion rate within the boundaries of farms with WFPs implemented prior to 1995 and limited to the extent of dairy and sheep and beef farming. The resulting reduction in erosion rates due to WFPs was merged with NZeem® for 2012 which incorporated changes in forest cover between 1996 and 2012 (from LCDB). This was used as the baseline for the assessment

Table 2. Summary of farm plan and riparian exclusion mitigation data by region.

Region	Area of region (km^2)	Area with farm plans (km^2)		% of region with farm plans		Major streams fenced in 2015 (%)
		1995	2015	1995	2015	
Northland	12,510	822	822	6.6	6.6	71
Auckland	4941	1	1	0.03	0.03	64
Waikato	24,578	216	3732	0.9	15.2	80
Bay of Plenty	12,280	335	1874	2.7	15.3	83
Gisborne	8386	68	611	0.8	7.3	29
Hawke's Bay	14,191	660	1086	4.7	7.7	45
Taranaki	7254	5	2021	0.07	27.9	77
Manawatu-Wanganui	22,220	0	5225	0	23.5	62
Wellington	8120	96	443	1.2	5.5	52
Tasman	9650					59*
Nelson	424					
Marlborough	10,470					34
West Coast	23,320					65
Canterbury	45,207					62
Otago	31,905					48
Southland	30,093					76
Total	265,551	2204	15,816	0.8	6.0	

* Tasman Nelson data were supplied as aggregated data.

of the effect of post-1995 WFPs and riparian retirement. For 2015, the analysis was also limited to the extent of dairy and sheep-beef farming, which differs from its extent in 1995. Results were summarised by region and farm typologies. Estimates of changes in sediment load (t) are affected by both the reduction in erosion rate as a result of erosion mitigation and the extent of the different types of pastoral farming. Results are therefore discussed in terms of mass sediment load (t) and sediment load per unit area (sediment yield, t km^{-2}) to establish the effect of erosion mitigation independent of any changes in areas of dairy or sheep-beef farming.

Results & discussion

N and P losses and mitigation effects per typology

Dairy farms

An important premise behind the typology approach taken in this study was that certain mitigations would be more effective and therefore relevant within some typologies than others, due to the contrasting vulnerabilities caused by soil drainage, wetness and slope factors. Calculations of N loss reductions per dairy farm typology for each mitigation are shown in Figure 1 and Supplementary Table S1, respectively; for brevity, only results for 2015 are presented. The potential mitigation effects apparent in Figure 1 are only briefly discussed here to illustrate why we consider dairy farm typology to be a useful categorical approach that can guide planning actions to manage and mitigate contaminant losses to water. A more detailed analysis and discussion of these potential mitigation effects is presented in the companion paper by McDowell et al. (2020).

Some general conclusions are evident in the N loss reductions plotted in Figure 1. The first is that relatively large load reductions are potentially achievable for the three Irrigated farm typologies where source (due to N inputs) and transport (due to irrigation inputs) risk factors are relatively high. The largest potential N reduction is observed

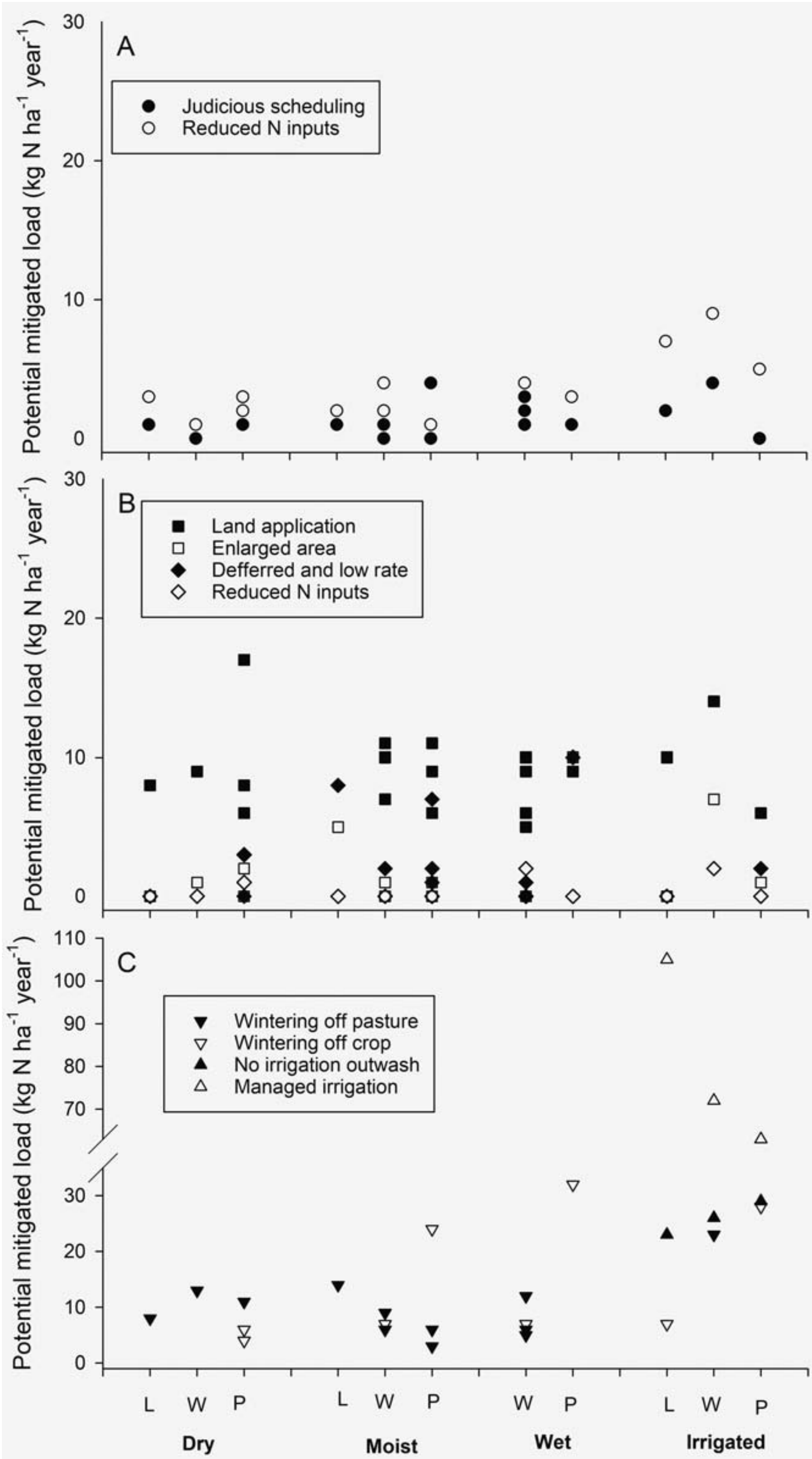

Figure 1. Estimated potential N loss reductions achievable following the implementation of (**A**) N fertiliser, (**B**) effluent and (**C**) irrigation and wintering mitigation practices. Slope (flat and rolling) and temperature (cool and warm) typology responses are lumped within Drainage (L = Light, W = well-drained, P = poorly-drained soils) and Wetness typology categories, where relevant.

for the Light Irrigated typology when irrigation scheduling was changed to an 'active' management regime. This is where applications are scheduled according to need, rather than at fixed intervals (Figure 1C). Preventing irrigation outwash from flood-irrigated farms also delivered relatively substantial reductions in estimated N (and P) losses to water from irrigated farm typologies. Avoiding wintering stock on crop appeared to be a particularly effective strategy for reducing N losses to water from farms with Poorly-drained soils located in Moist and Wet environments. Land application of FDE was the next most important mitigation for reducing N (and P) loss to water, although the effects of typology attributes were inconsistent and of less relevance, as expected for this mitigation. Other than wintering off pasture, the potential N load reductions for the remaining individual measures were generally relatively small. The effects of typology risk factors for P mitigation were less evident (Table S2). Exceptions to this were the relatively large potential P load reductions estimated in response to improved irrigation management practices on Irrigated farm typologies, and the response to improvements in P fertility management for some typology units. The inconsistent effects noted for P fertility management improvements may be attributable to the confounding effects caused by the contrasting soils that were selected as the predominant soil types within a given typology. This can be illustrated for the Low solubility P fertiliser measure documented in Table S2, where increased wetness expectedly led to greater potential P load reductions for Poorly drained typology units in Warm-Flat locations. This did not appear to be the case for Poorly drained typology units in Cool-Flat locations where little reduction was estimated due to the more resilient nature of soils in these typologies and their greater ability to retain P. The large reductions noted for improved irrigation management reflect the starting scenario for irrigated farms in 1995 that were assumed to be under border dyke irrigation and potentially discharging large quantities of P in irrigation outwash. Also of note in Table S2 are the relatively large reductions in P losses that are estimated in response to fencing of streams to exclude livestock.

Sheep and sheep-beef farms

The effects of modelled mitigations for reducing N losses to water from sheep and beef farms were relatively small when expressed on a per hectare basis (Table S3). This was expected, given that most of the measures selected for assessment targeted losses of other contaminants such as P, sediment and FMOs. Land retirement was the most effective N and P mitigation scenario evaluated, reducing farm scale losses of P up to 0.65 kg P ha^{-1} yr^{-1}. However, the equivalent reductions in N losses for this mitigation scenario were small in most cases, at less than 1 kg N ha^{-1} yr^{-1}. The modelled impacts of stream fencing on N and P losses were also negligible in most cases and showed little difference between the two time periods considered here (data for 1995 not presented). Attaining optimal soil P test levels and judicious timing of P fertiliser applications, to avoid periods when the risk of surface runoff is high, had a minor effect on estimated P losses to water, as modelled by Overseer (generally less than 0.1 kg ha^{-1} yr^{-1} overall). Although the absolute amounts of N fertiliser used on sheep and beef farms (average of 3.2 t N yr^{-1} per farm) increased compared to 1995, the effect of improved N fertiliser scheduling was small and reflects the relatively low rates of N fertiliser use when expressed on a per hectare basis.

Estimates of N and P mitigation effectiveness for 'typical' NZ farms

Area-weighted means of mitigated losses were calculated to identify which measures have been most effective at reducing N and P losses from farms at a national scale. One of the key messages illustrated in Table 3 and Figure 2 is the relatively large rate of N mitigation modelled for irrigated dairy farms. Much of this effect can be attributed to the reduced transport potential of N and P due to reduced over-watering (Kitchen et al. 2008). Prevention of irrigation by-wash conveying P and faecal material into ditches and streams (Monaghan et al. 2009) made a small but significant contribution to the P mitigation illustrated in Figure 3. Improved management of FDE (i.e. the shift to land application of FDE and used of deferred irrigation scheduling practices) was the next most effective measure for mitigating N losses to water from New Zealand dairy farms and was the most effective measure for mitigating P losses. Stream fencing was then the most effective measure for mitigating both N and P losses from dairy farms at a national scale in 2015. While quantitative estimates of their effectiveness are difficult to derive, as discussed in the Supplementary information, farm-scale analysis reported elsewhere indicates that stream fencing and FDE management will also have a significant effect on reducing faecal microbial losses from dairy farms (Muirhead et al. 2010, 2011; Muirhead 2015). Ranked in order of effectiveness from highest to lowest, the measures that have delivered the greatest reductions in farm N losses to water are: improved water irrigation management, effluent application to land, stream fencing, enlargement of FDE-treated areas, reduced inputs of N fertiliser, off-paddock wintering, judicious timing of N fertiliser applications and deferred and/or low rate FDE irrigation to land (Figure 2). For P, the order of effectiveness is: FDE irrigation to land, stream fencing, preventing irrigation by-wash, reduced inputs and judicious timing of P fertiliser applications, and deferred FDE irrigation to land (Figure 3).

Area-weighted means of mitigated N and P losses from sheep and sheep-beef farms are shown in Figures 4 and 5, respectively. As noted for individual typology units, the

Table 3. Area-weighted estimates of reductions (%) in N and P losses to water from dairy farms due to the implementation of single mitigation measures. The effectiveness of P mitigation measures was in most cases calculated assuming FDE was applied to land.

Mitigation		% reduction in N loss	% reduction in P loss
Stream fencing		3	26
Phosphorus fertiliser	Judicious application		2
	Optimum Olsen P		2
	Low Solubility P		1
Nitrogen Fertiliser	Judicious application	2	
	Reduced N inputs	2	
Effluent management	Land application[1]	18	68
	Optimum area	5	2
	Deferred and low rate application	<1	<1
	Reduced N inputs to effluent area	<1	
Off paddock wintering	Off-paddock instead of on crop	2	
	Off-paddock instead of on pasture	2	
Irrigation management[2]	No outwash	23	60
	Managed irrigation application	34	24

[1]effectiveness calculated by comparing scenarios with 2-pond FDE discharge or land application of FDE.
[2]effectiveness calculated for irrigated land areas only.

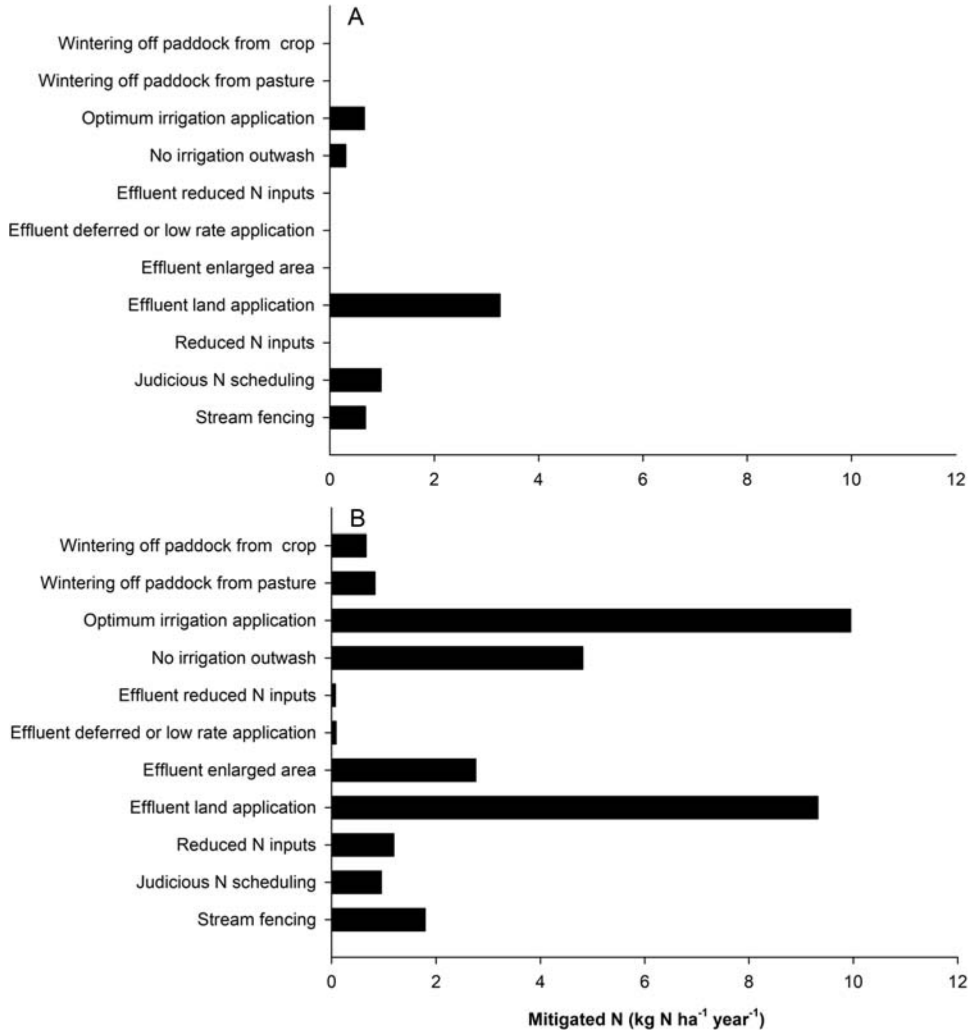

Figure 2. Modelled estimates of actual mitigated N losses to water (kg N ha^{-1}yr^{-1}) on dairy farms for (**A**) 1995 and (**B**) 2015. Note that the irrigation mitigations apply to irrigated typologies only; remaining estimates of mitigation effectiveness are calculated as area-weighted means of remaining typologies.

effects of modelled mitigations for reducing N losses to water on a per hectare basis were minor (Figure 4). Of the P loss mitigations considered, land retirement had the most influence on P losses (area weighted mean of just under 0.2 kg ha^{-1} yr^{-1}). Improved timings of fertiliser applications, to avoid periods when the risk of surface runoff is high, and optimal soil P test levels generally had minor effects on modelled P losses to water, while stream fencing effects were negligible. Stream fencing is likely to be the most effective mitigation for reducing faecal microbial contamination but actual effectiveness is likely to be highly variable (Muirhead 2019) and implementation by this sector has been relatively low (Table 1) (see also Brown 2017; MfE 2018).

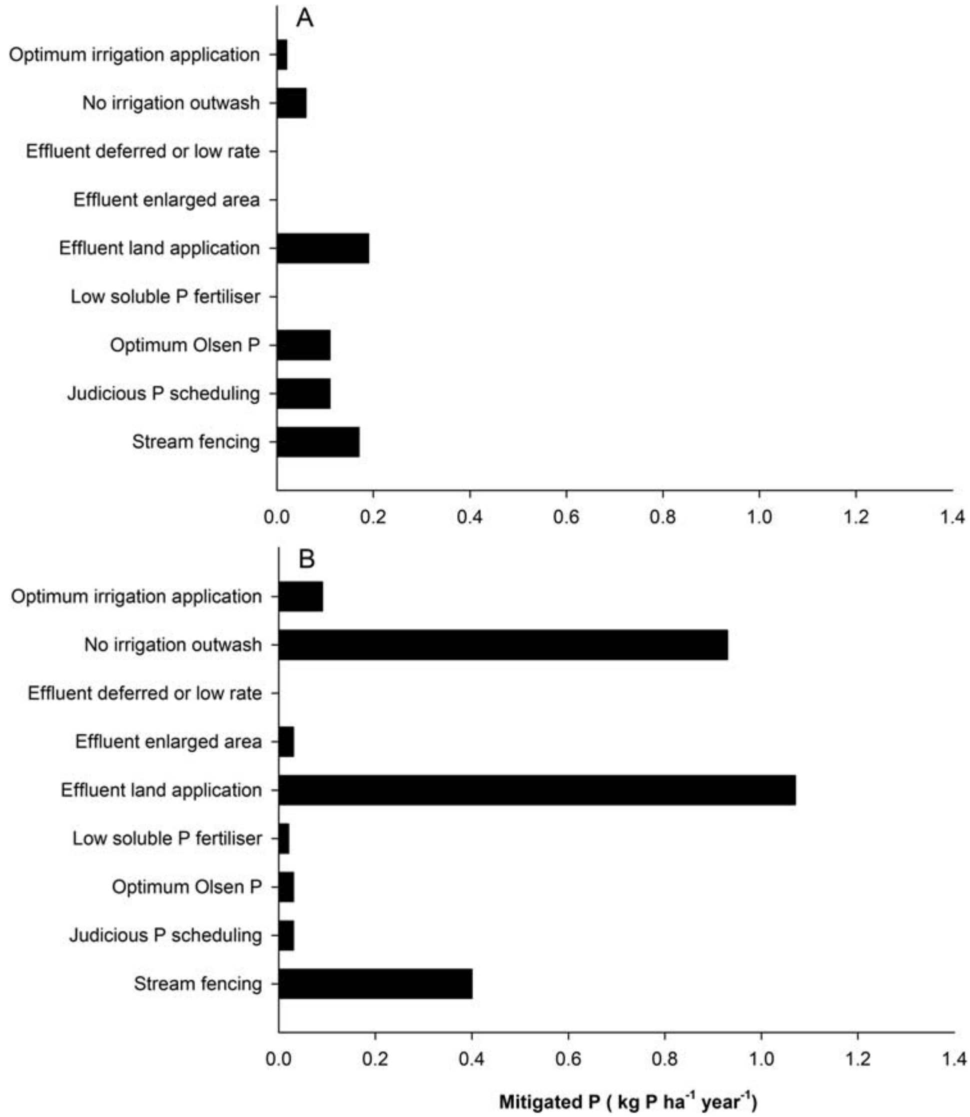

Figure 3. Modelled estimates of mitigated P losses (kg P ha^{-1}yr^{-1}) on dairy farms for (**A**) 1995 and (**B**) 2015. Note that the irrigation mitigations apply to irrigated typologies only; remaining estimates of mitigation effectiveness are calculated as area-weighted means of remaining typologies. For context, the calculated mean annual P loss estimates from modelled Base farms in 1995 and 2015 are 1.8 and 1.4 kg P ha^{-1}yr^{-1}, respectively.

Sediment losses and mitigation effects

As erosion rates in New Zealand are heavily influenced by natural factors such as rainfall, geology and slope (Basher 2013), changes in sediment load reflect both changes in the extent of pastoral farming and the secondary influences of soil conservation works (afforestation, WFPs and riparian exclusion). Here we briefly provide an overview of the extent of mitigation implementation and the relative importance of the key sediment mitigation measures considered in our analysis.

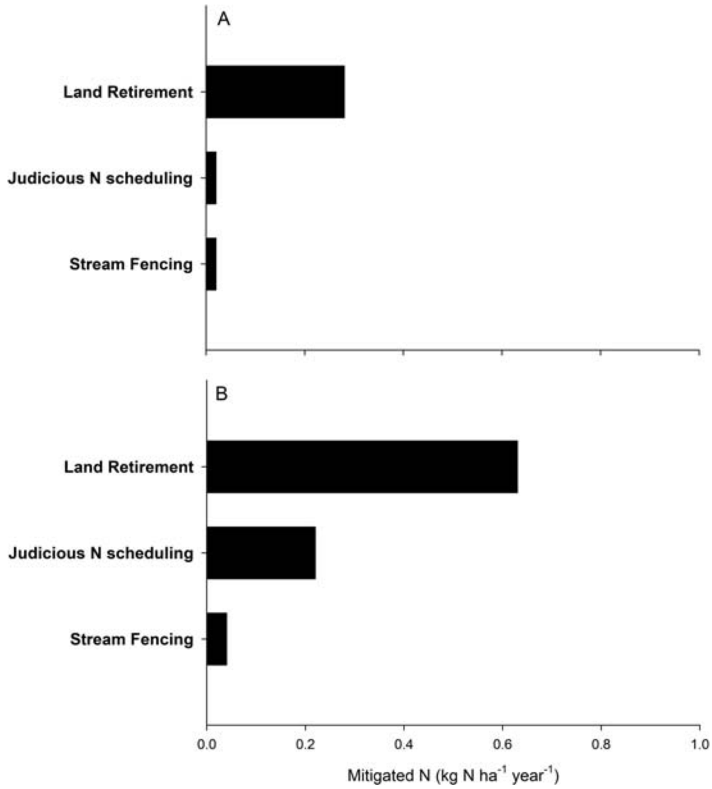

Figure 4. Modelled estimates of mitigated N losses to water (kg N $ha^{-1}yr^{-1}$) from sheep and beef farms for (**A**) 1995 and (**B**) 2015.

Low implementation of WFPs appears to heavily constrain the effect on reducing sediment losses. This varied widely between different regions; although it was noted to have increased significantly in the North Island between 1995 and 2015, the percentage of farmland with WFPs over the whole country increased from 0.8% to 6.0% (Table 2). The regions with the highest percentage of land with WFPs are Taranaki (28%), Manawatu-Wanganui (24%), Bay of Plenty (15%) and Waikato (15%). In the highly erodible

Table 4. Summary of changes in sediment load and yield for pastoral farmland between 1995 and 2015.

		1995			2015			Change in load
		Area (km^2)	Sediment load (t)	Sediment yield (t km^{-2})	Area (km^{-2})	Sediment load (t)	Sediment yield (t km^{-2})	(2015–1995) (t)
Dairy	NZ	12,178	4.3×10^6	351	22,549	5.8×10^6	259	1.6×10^6
Sheep-Beef	North Island	37,428	65.7×10^6	1756	32,671	45.4×10^6	1388	-20.4×10^6
Sheep-Beef	South Island	62,434	19.3×10^6	309	49,984	12.2×10^6	244	-7.1×10^6
Sheep-Beef	NZ	99,862	85.0×10^6	851	82,655	57.5×10^6	696	-27.5×10^6
Dairy+SB	NZ	112,040	89.3×10^6	797	105,204	63.4×10^6	602	-25.9×10^6

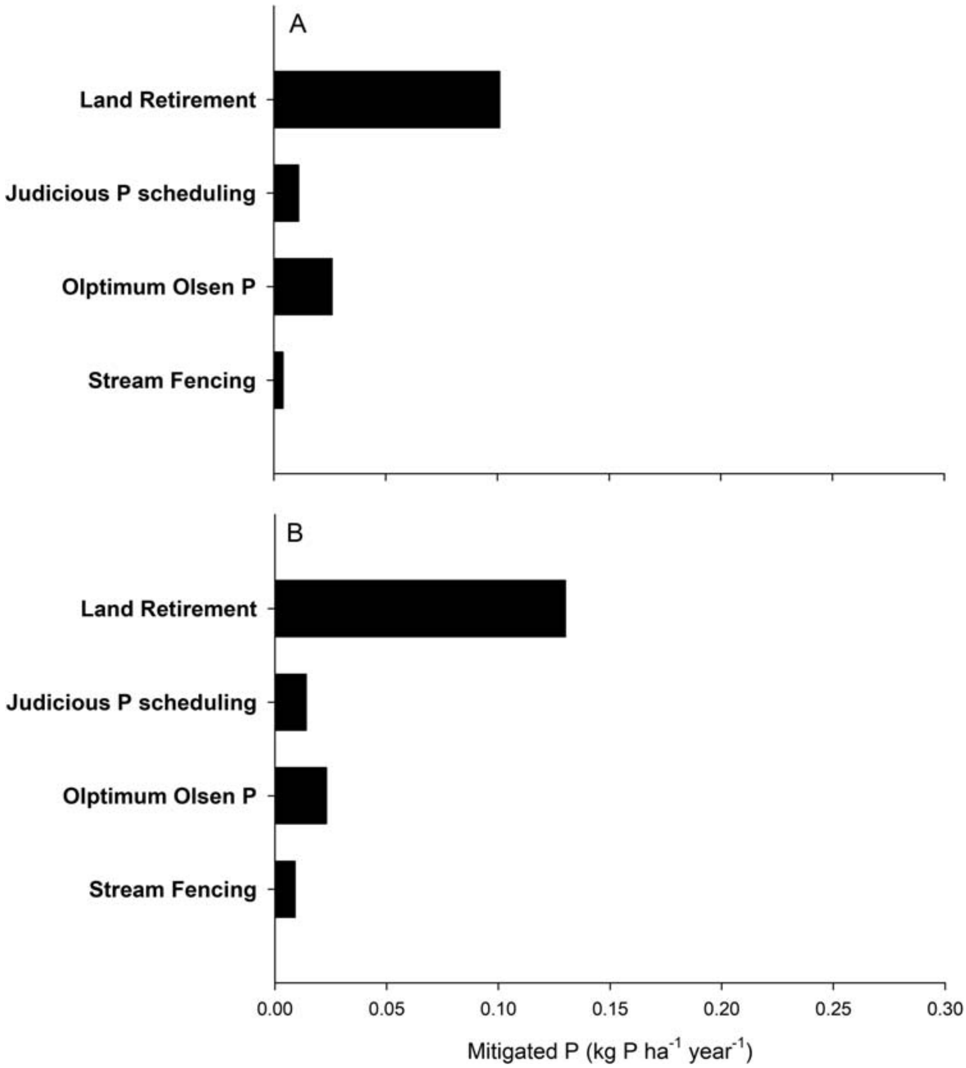

Figure 5. Modelled estimates of actual mitigated P losses (kg P $ha^{-1}yr^{-1}$) on sheep and beef farms for (**A**) 1995 and (**B**) 2015.

Gisborne area, much of the change in erosion mitigation has been achieved by conversion of pastoral farmland to exotic forest because of the government-funded East Coast Forestry project, with about 604 km^2 of new forest established (Phillips et al. 2013). In recent years fencing of major streams has been a high priority for pastoral farming (McKergow et al. 2016), especially dairying, with the result that most regions now have more than 50% of major streams fenced and some as much as 80% (Waikato and Bay of Plenty; Table 2). Implementation of WFPs and riparian exclusion of stock contributed to reductions in sediment yields within 13 of the 17 sheep-beef farm typologies. These measures are estimated to have decreased area-weighted calculations of sediment yields from 851 t km^{-2} in 1995 to 696 t km^{-2} in 2015 (Table 4). Stock exclusion from riparian margins has reduced bank erosion on many dairy farm typologies, with almost two thirds showing reductions in sediment yield. The reduction in area-weighted estimates of dairy farm sediment yields from 351 t km^{-2} in 1995 to 259 t km^{-2} in 2015 (Table 4) is primarily attributable to this stock exclusion measure. Recent work has shown that small streams (not major streams) contribute much of the sediment load at a catchment scale (McDowell et al. 2017). Additional reductions would have been possible if stock were excluded from small streams; however, after considering the considerable costs that this would put on landowners, recent legislation focuses on major streams (MfE 2020). We chose to emulate this policy when considering our implementation of fencing and stock exclusion.

Mitigated loads for all pastoral land

Our analysis sought to quantify the extent of N, P and sediment mitigation that has occurred on pastoral farms in New Zealand. Such an assessment ideally needs to consider changes in farmed areas and in land use intensity that have been distinguishing features of recent dairy farming activity in NZ (LIC 2015). Results presented in Figures 2 and 3 indicate that appreciable quantities of both N and P have been mitigated on dairy farms due to the measures discussed above. This is estimated to have reduced P losses between 1995 and 2015 within most (16 of 20) of the dairy farm typologies evaluated here. However, due to the effects of farm intensification that have occurred between 1995 and 2015 (see Table 1 of Monaghan et al. 2021), it is evident that mitigation measures have not been enough to fully offset increases in N losses to water, with 10 of the 20 dairy typologies showing increases in per hectare losses of N to water; weighted for typology areas, mean losses increased from 46 to 49 kg N ha^{-1} yr^{-1}, or by 7%. Coupled with this intensification has been a significant expansion of dairy farmed area, in some cases into areas with Light soils that are more vulnerable to N loss. The combined effects of increases in farmed areas and per hectare losses of N are projected to have increased total N losses from New Zealand dairy farms from 56 to 111 Gg yr^{-1}, or by 98%. Similar estimates for P indicate that loads increased from 2.2 to 2.4 Gg yr^{-1} (a 10% increase), again reflecting how an increase in dairy-farmed area more than off-set the P mitigation documented earlier; this increase in dairy-farmed area had a similar effect on sediment load.

Expressed on a per hectare basis, the potential for mitigating N losses from sheep and beef farms is low relative to that for dairy. This is partly due to the reduced number of measures available to sheep-beef farmers and to the lower N leaching values estimated for this land use. Owing to the greater areal extent of sheep and beef farms, these small effects (mitigation or intensification) can add up to a large cumulative effect at national level, however; for 2015, we estimate sheep-beef farms represented 47 and 73% of the N and P loads from pastoral land, respectively. The combined effect of a reduction in sheep-beef farmed area (from 10 M ha in 1995 to 8.3 M ha in 2015) and the modest amount of P mitigation mentioned above would suggest that P loads decreased from 9.3 to 6.4 Gg yr^{-1} (a 31% reduction) between 1995 and 2015; in the case of N, the net effect of reduced area and the slight increase in N loss per hectare suggests that N loads to water from areas used for sheep-beef farms decreased from 112 to 99 Gg yr^{-1} (a 12% reduction).

If the combined effects of changes to farmed areas and per hectare yields are considered for all pastorally-farmed land in New Zealand, we calculate that N loads increased from 169 to 210 Gg yr^{-1} between 1995 and 2015 (+25%) because of an expanding dairy industry as already noted. This increase has occurred despite a small reduction (from 11.2 to 10.5 M ha) in pastorally-farmed land. Equivalent estimates for P indicate that loads decreased from 11.5 to 8.8 Gg yr^{-1} (−23%) due to the mitigation effects noted above for sheep-beef farms.

At a national level, the sediment load from sheep-beef farming is calculated to have decreased from 85.0 Mt in 1995 to 57.5 Mt in 2015, or by 25.9 Mt (29%). The largest sediment load decreases were estimated for the erosion-prone hill country and hard hill country on the East Coast of the North Island and Northland – Waikato – Bay of Plenty, and in the South Island high country in Otago-Southland (Supplementary Figure 1A). The hill country and hard hill country typologies on the East Coast of the North Island contributed 53% of the total sediment load from pastoral farms in 2015, suggesting an on-going need for erosion mitigation in this region to reduce these loads further. If all pastorally-farmed land is considered, sediment losses have fallen from 89.3 Mt in 1995 to 63.4 Mt in 2015, a decrease of 25.9 Mt. Afforestation of about 1370 km^2 of grassland has been the single-most important measure to achieving this reduction, accounting for 13.4 Mt. The remainder of the load reduction (12.5 Mt) can be attributed to the mitigation achieved by the increased implementation of WFPs and stock exclusion from riparian zones.

An important goal of our analysis was to determine how much progress has been made in mitigating and off-setting the impacts of pastoral farming activities on water quality, against a backdrop of considerable change in land use and farm intensification. A pertinent aspect of this consideration is the projection of N, P and sediment losses, assuming that no mitigation had been undertaken over the past 20 years, i.e. how large could losses in 2015 have been? These projections are shown in Figure 6 and portray area-weighted estimates of N, P and sediment yields for 2015 with (solid bars) and without (including dashed bars) mitigated loads that we have calculated for the period between 1995 and 2015. One purpose of these projections is to be able to recognise

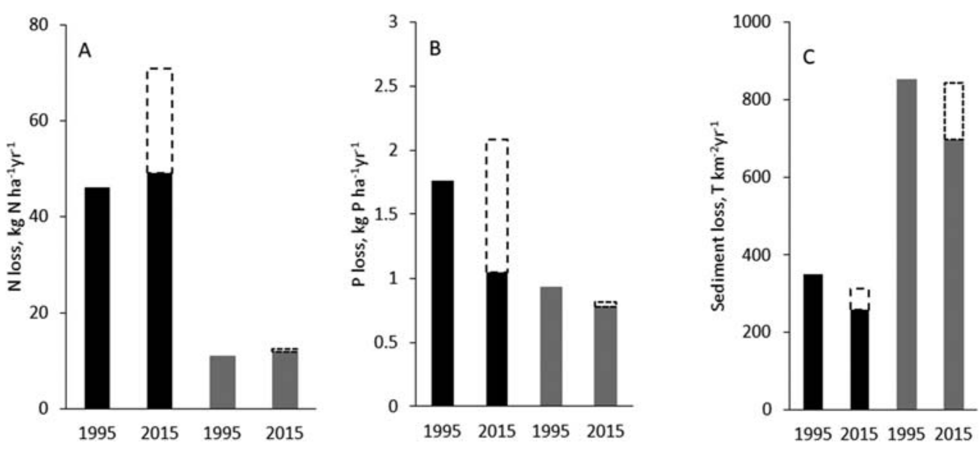

Figure 6. Area-weighted estimates of (**A**) N, (**B**) P and (**C**) sediment yields from dairy (black bars) and sheep-beef (grey bars) farms with and without (including dashed bars) mitigated loads calculated for the period between 1995 and 2015.

the contributions that combined mitigation actions have delivered to improved water quality outcomes, many of which have incurred significant investment in both time and financial cost. It is apparent from Figure 6 that this investment has been particularly beneficial for minimising losses of N and P from dairy farming systems; without mitigation, mean annual losses per hectare would have been 45 and 98% greater than present, respectively. Implementation of measures to control sediment losses has had important benefits for both dairy and sheep-beef farming systems; extending their implementation to targeted erosion-prone landscapes will be an important step towards cost-effectively reducing loads still further.

Limitations of the study

The complexity and uncertainties associated with the mitigation assessments undertaken here are recognised as important limitations of the findings discussed above and can be categorised into at least three areas. The first concerns challenges associated with trying to derive data to describe what has likely happened at a farm scale, which is the scale where most mitigation decisions are considered and implemented. Assessments therefore rely on assumptions that need to be made about 'typical' human decision-making and behaviour, guided by varying degrees of insight that can be discerned from farm survey information, production statistics, industry records and information sources held by regional government. The analysis reported here heavily depends on the representativeness of farm attributes reported for the typologies described in Monaghan et al. (2021). The sediment mitigation analysis relied heavily on data supplied by regional councils for implementation of soil conservation works through time, the quality of which was highly variable between regional councils. In addition, the assessment of riparian exclusion was based on the SRDM (Brown 2017), which only provided regional average data on implementation of riparian exclusion measures.

An additional area of uncertainty attached to the farm scale assessments reported here is the ability of the modelling tools to quantify contaminant losses from different landscapes and under contrasting farm management actions. We acknowledge that while the Overseer model provides reasonably robust estimates of farm-scale losses of N to water, estimates of P losses from farms heavily depend on spatial considerations that are less well represented by this tool. The sediment modelling used an empirical model that does not include process representation and we had to make a crude assumption of the relative significance of hillslope and bank erosion to assess the reduction in sediment generation from riparian exclusion; the analysis could have been considerably improved if a more process-based tool such as that described by Dymond et al. (2016a) had been employed. We also note that modelling tools to conduct this analysis for faecal microbes have not yet been developed due to a lack of fundamental knowledge of faecal microbial losses to water.

Another area of uncertainty concerns the difficulties encountered when trying to scale assessments to catchment, regional or national levels. The typology approach used here was deemed the most tractable method for aligning sufficiently insightful farm-scale information with spatial representations that reflected either the inherent vulnerability of N and P loss to water (for dairy farms) or production intensity (for sheep and beef farms). Although this provided a reasonably large number of potentially representative dairy farm typologies, sufficiently detailed management information was only available for up to 20 of these and caution is therefore noted for calculations of area-weighted estimates of N and P loss under the mitigation scenarios that have been considered.

Notwithstanding the above limitations, there are some key messages that can be extracted from the analyses that are supported by literature evidence. The first key message is that whilst mitigation measures have not been enough to offset the effects of an expanding and intensifying dairy herd, they have been important for constraining rates of N losses from pastoral land. These observations generally agree with those reported for several catchment scale studies where concentrations and/or loads of N in water have increased in dairy farmed regions (Monaghan et al. 2007, 2009; Wilcock et al. 2013; Wright-Stow and Wilcock 2017) or for locations where land use is categorised as 'intensive pastoralism' (Larned et al. 2016; Julian et al. 2017). In many cases these studies also report improving trends for NH_4-N, P (total and dissolved reactive forms) and clarity, which we can perhaps attribute to some of the mitigation measures considered here, in particular those where effluent and fertiliser management practices have improved and riparian protection has increased (McDowell et al. 2019).

Conclusions

This analysis estimated the effectiveness of on-farm mitigations, implemented over the last 20 years, for reducing contaminant losses to water in New Zealand. The mitigations applied on-farm have reduced N and P losses from individual farms. In the cases of P and sediment, these mitigations have resulted in overall reductions in losses at a national scale. For N, however, the mitigations have not been enough to offset both (a) the increase in land now used for dairy farming and (b) intensification of pastoral land use, resulting in an increase in N losses to water at the national scale. Our analysis also shows how N loading to water would have been significantly greater in the absence of mitigation. There was insufficient knowledge of faecal microbial losses to conduct a similar assessment. This analysis has highlighted the challenges of relying on mitigating contaminant losses from land-use to achieve water quality goals, and of not considering the effects of land-use change and intensification.

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