Marine and Freshwater Research, 2021, **72**, 451–455
https://doi.org/10.1071/MF20201

Supplementary materials

Implications of water quality policy on land use: a case study of the approach in New Zealand

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Our analysis drew from previous work by Monaghan *et al*. (2020*a*) and McDowell *et al*. (2020) that quantified nitrogen (N) and phosphorus (P) losses from different farm typologies (Monaghan *et al*. 2020*b*) and applied actions to mitigate these losses. We translated these losses and actions into potential dissolved inorganic N DIN) and dissolved reactive P (DRP) concentrations.

The farm typologies were distributed across New Zealand within catchments as defined by catchment-specific segments of the River Environment Classification (REC) (Snelder *et al*. 2005). This distribution and subsequent modelling of losses estimated N and P yields (kg P ha^{-1} $year^{-1}$) for each segment. We restricted our farm typologies to those in dairy and sheep and beef – although one sheep and beef typology contained 66% of arable land in New Zealand. Additional analysis (below) accounted for land in horticulture. We did not adjust nutrient losses for land in native or exotic forestry within a catchment as these land uses contribute less nutrients to catchment loads than other land uses and therefore did not need to be mitigated (McDowell and Wilcock 2008; Baillie and Neary 2015). The mitigated load therefore only applied to the area of land in dairy or sheep/beef (plus 66% of arable land). Land in native bush was excluded from our analysis as this land use would be excluded from regulation under proposed exemptions for natural conditions (Ministry for the Environment 2017). Our analysis did not consider land use change.

The analysis of Monaghan *et al*. (2020*a*) and McDowell *et al*. (2020) applied a suite of established and developing strategies to mitigate N and P losses from farms (Table S1) to each of these farm typologies, thereby generating two reduced loss rates. These mitigation scenarios assumed 100% implementation of 1) established strategies to the baseline year with immediate effect, and; 2) developing strategies to the baseline year that were effective by 2035. We refer to these scenarios as ‘established’ and ‘developing’.

Table S1. List of established and developing strategies used to mitigate N and P losses from dairy and sheep and beef land

Refer to Monaghan *et al*. (2020*a*) and McDowell *et al*. (2020) for a full explanation of their suitability to an enterprise, description and efficacy to reduce N and P losses.

Mitigation action	Land use
Established mitigation (full implemented 2015)	
Riparian protection	Dairy, Sheep/beef
Effluent management	Dairy
Off paddock management	Dairy
Irrigation management	Dairy
Fertiliser management	Sheep/beef
Land retirement	Sheep/beef
Developing mitigations (implemented by 2135)	
Retention dams, bunds or sediment traps	Dairy
Strategic grazing of pasture within critical source areas (CSAs)	Dairy
Strategic grazing of crops within CSAs	Dairy
Tile drain amendments	Dairy
In-stream sorbents	Dairy
Alum applied to pasture or crops in CSAs	Dairy
Controlled release fertiliser	Dairy, Sheep/beef
Variable rate fertiliser	Dairy, Sheep/beef
Variable rate irrigation and fertigation	Dairy
On-off grazing in autumn/winter	Dairy
Edge of field attenuation	Dairy, Sheep/beef
Controlled drainage	Dairy, Sheep/beef
Constructed wetlands	Dairy, Sheep/beef
Decreasing N inputs (fertiliser and supplements) by half	Dairy
Catch crop	Dairy
Nitrification inhibitors	Dairy
Increasing the area in plantation forestry from 12.5 to 25% of the property	Sheep/beef

The analysis of Monaghan *et al*. (2020*a*) and McDowell *et al*. (2020) generated losses as yields, but the proposed DIN and DRP bottom lines are set as concentrations. In previous estimates of the effects of land use change and mitigation actions on N and P losses it has been assumed that a change in the load for a catchment would result in a proportional change in the median concentration (Elliott *et al*. 2014; McDowell 2014). We assumed that mitigation actions decreased DIN and DRP losses the same amount as TN and TP losses. However, we recognise that some actions may preferentially decrease either a dissolved or particulate fraction of N or P.

We used median DIN and DRP concentrations for the period 2013–2017 for each catchment that intersected a typology using data available at: https://data.mfe.govt.nz/table/99871-river-water-quality-modelled-state-20132017/. These medians were used to set the 2015 baseline for DIN and DRP concentrations nationally.

In calculating reductions in median DIN and DRP concentrations for the established and developing scenarios we used the same area- and land use-weighted percentage reductions as used in calculating mitigated loads by McDowell *et al*. (2020). However, to fully explore the implications of potential policy bottom lines at a catchment scale we expanded our consideration of land uses to also include horticultural land and the 34% of arable land outside of Sheep/beef typology 17. Collectively, horticultural and the remaining arable land amount to < 300,000 ha and unlikely to influence our estimates of national catchment load reductions but may impact on an ability to meet a bottom line in some small catchments. We therefore adjusted catchment medians by assuming an area-weighted 20% decrease in losses from these lands for the 2015 potential scenario and by 30% for the 2035 scenario. Due to a paucity of data and the wide range of arable and horticultural land uses in New Zealand, we assumed that losses of DIN and DRP were like those of pastoral typologies in the same catchment. The limited data available supports this assumption. For instance, Norris *et al*. (2017) measured median TN and TP losses in leachate from topsoil (*c*. 0–20 cm) across eight arable and horticultural systems of 30 kg N ha^{-1} $year^{-1}$ and 0.4 kg P ha^{-1} $year^{-1}$ (doubled to account for surface runoff losses), similar to N losses measured from dairy farms and P losses from sheep farms (McDowell and Wilcock 2008). Very few data were also available for the effectiveness of measures to mitigate N and P loss from New Zealand arable and horticultural systems. Of that available, losses were reported to decrease from 5% due to changes in fertiliser-N rates and crop rotations to 75% due to the prevention of sediment (and P) losses from erosion-prone critical source areas. We chose decreases of 20 and 30% as a conservative estimate of mitigation effectiveness in the 2015 potential scenario with an additional 10% decrease achieved by the development of new mitigation measures in the 2035 scenario. These decreases are in line with mitigation effectiveness reported in similar systems in England (Zhang *et al*. 2017).

The output of this analysis on a regional basis is given in Table S2. It is important to note that although we included the efficacy of all developing mitigations in the 2035 scenario there is also potential for new mitigations to be developed and implemented, and land use and intensities to change. This suggests that our analysis may be pessimistic; however, we have assumed 100% implementation of developing mitigations, which is unlikely to be the case.

Table S2. Percentage of catchments exceeding proposed bottom lines for dissolved inorganic nitrogen (1 mg L^{-1}) and dissolved reactive phosphorus (0.018 mg L^{-1}) in each region of New Zealand under each scenario

Values in parentheses represent the total area **meeting** proposed bottom lines (km^2) in each region. Note that if regions with high natural DRP concentrations (Auckland, Bay of Plenty, Gisborne, Northland, Taranaki and Waikato) were exempted from the originally proposed targets and, instead were meeting a higher but unknown concentration bottom line, the remaining area exceeding the bottom line was 16% in the 2015 scenario, reducing to 13 and 9% in the 2015 and 2035 mitigation scenarios respectively

Region			DIN			DRP	
	Area (km^2)	2015 baseline	2015 established	2035 established + developing	2015 baseline	2015 established	2035 established + developing
Auckland	347983	4.4 (332701)	3.9 (334181)	2.9 (337852)	35.6 (224123)	17.9 (285672)	13.5 (300998)
Bay of Plenty	457595	2.7 (445287)	2.5 (446022)	1 (452867)	42.1 (264933)	26 (338595)	18.2 (374361)
Canterbury	3428458	17.8 (2819065)	15.7 (2890855)	12.4 (3003174)	11.2 (3042966)	8.3 (3145461)	6.5 (3205596)
Gisborne	647758	<0.1 (647437)	<0.1 (647545)	<0.1 (647545)	6.3 (606979)	3.7 (623814)	3.2 (626977)
Hawke’s Bay	983153	0.3 (980342)	0.2 (980827)	0.1 (981778)	40.2 (587853)	25.1 (736568)	17.9 (807063)
Manawatu-Wanganui	1712110	1.2 (1691474)	0.8 (1699313)	0.4 (1705516)	28.2 (1229855)	20.9 (1354221)	15.9 (1439291)
Marlborough	726146	<0.1 (725778)	<0.1 (726032)	<0.1 (726032)	3.6 (700004)	2.1 (711090)	1.7 (713609)
Nelson	14523	<0.1 (14524)	<0.1 (14524)	<0.1 (14524)	2.3 (14194)	1.9 (14244)	1.9 (14244)
Northland	927748	1.3 (916023)	0.6 (922560)	0.2 (925879)	34.4 (608613)	17.1 (769389)	11.5 (820738)
Otago	2653891	0.9 (2629609)	0.4 (2644440)	0.2 (2648475)	17 (2203381)	14.5 (2268590)	12 (2335235)
Southland	1295745	19.4 (1044793)	18 (1063347)	14.7 (1105366)	31.4 (888527)	24 (984909)	18.2 (1060189)
Taranaki	564254	6 (530219)	3.2 (546229)	1.5 (555642)	38.8 (345407)	27 (411839)	14.8 (480706)
Tasman	294460	0.1 (294041)	<0.1 (294328)	<0.1 (294328)	8.7 (268748)	7.6 (272159)	6.4 (275632)
Waikato	1735193	6.6 (1620333)	3.6 (1671709)	1.8 (1703127)	54 (797799)	40.6 (1031252)	26.1 (1282252)
Wellington	591593	3.1 (573513)	2.3 (577778)	1.3 (583833)	18.9 (479813)	11.3 (524844)	7.1 (549448)
West Coast	361947	1.2 (357413)	0.6 (359771)	0.3 (360767)	0.2 (361197)	0.1 (361628)	0.05 (361750)
Nationally	16672249	6.7 (15622552)	5.5 (15819461)	4.2 (16046706)	24.6 (12624392)	17.4 (13834275)	12.5 (14459379)

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