Authors’ response to Editor’s and Reviewers’ comments

Editor comments:

I also acknowledge that the manuscript was seriously revised and has substantially be improved. Nevertheless, I still see two major deficiencies. The first is the length of the manuscript, which is partially due to the fact that the results and discussion contain side stories that are not essential to the paper and distract the reader (see detailed comments below). Please note that what I call side stories here are not necessarily unimportant per se, but they are superfluous in the context of this paper.

We have shortened the paper according to your comments below and in many other places. We removed most of the catchment identifiers throughout the ms, except in parts of the Discussion where it is necessary and those that relate directly to Figure 5 where we point out specific catchments. We removed a couple of the ‘side stories,’ but kept the ones we felt were essential to the story of how river water quality responds to land use intensity, which requires a physiographic context. We justify these instances below.

The second deficiency relates to the actual content and focus of the paper. In this revised version you put the emphasis on land use intensity – at least in the title and the abstract. However, the actual result section consists only of one out of six subsection that specifically addresses land use intensity (sub-section 4.3) and sub-section 4.6 on multivariate is only about correlation between land use and water quality. Land use intensity is not dealt with.

We respectfully disagree with this assessment that land use intensity is not covered throughout the ms. We wrote the Introduction in a manner that first summarizes what has been done in land use-water quality relationships (i.e. observations) in order to develop and justify our hypothesis that land use intensity is a better predictor of water quality. Even when we discuss land uses, we put them within the context of land use intensity. For example, section 4.2 distinguishes between land uses that are intensively managed (high-producing grasslands and plantation forests) versus those that are not intensively managed (low-producing shrub/grassland and non-plantation forest). Further in section 4.2, we have to point out that areal coverage has not changed much so that we can make the case for land use intensity driving the changes in water quality. Another example is section 4.5 where we relate water quality to intensively managed grasslands, stock unit densities, and disturbance. We acknowledge that some small sections do not deal specifically with land use intensity, but these are mostly cases where we need to characterize physiographic variability in order to understand water quality changes with land use intensity in different environments. For example, water quality in catchments with high soil phosphate retention responds differently to agricultural land uses. Further, we make the connections between physiography and land use intensity (section 4.3). Section 4.6 does address land use intensity, indirectly when it reports relationships with high-producing grasslands and directly when it reports that stock unit density was the primary predictor for all four nutrient variables. Overall, keep in mind that we are covering both land use intensity and its effect on water quality. This is why the first section of the Discussion (5.1) covers water quality relationships and patterns. We relate land use intensity to physiography in section 5.2 and then bring everything together in section 5.3 which is all about land use intensity (i.e. livestock densities, fertilizer use, disturbance. This section is by far the longest section of the ms, the concluding section, and the most important. Our final point in this regard is that this is a true ‘earth systems science’ study (the focus of this journal) where we not only look at relationships between land use intensity and water quality, but take into account all aspects of the earth system such as climate, topography, soils, vegetation, and human-environment interactions. Nevertheless, we have revised some parts of the ms to make our discussion of land use intensity more explicit. Examples include 2nd sentence of section 4.2, 2nd paragraph of section 5.1, L27 of Abstract, and 1st sentence of section 5.3.3.

In my previous comments I asked explicitly for a clear focus on intensity: “Given the fact that Reviewer # 2 called for a clear focus of the manuscript and your suggested focus and effects of land use intensity, I strongly recommend that the result and discussion really concentrate on this aspect.” When evaluating the actual content of the results section of the revised version one has to state that the largest part does not deal with land use intensity. This discrepancy between title/abstract on the one hand and the actual content on the other hand, is annoying and evokes the impression that the revisions were only superficial. I can only accept this manuscript for publication if this aspects is seriously improved. I am convinced that a stronger focus will automatically lead to a shorter manuscript improving on the length issue.
See our reply above, and when reviewing our ms, please keep in mind that land use intensity includes livestock densities, fertilizer use, and disturbance, which are the focus of the ms. This is made clear in the 2nd sentence of the abstract and the Introduction (L90).

Detailed comments (Line numbers refer to the version with track changes of the Author's Response):
My line numbers refer to the version submitted on 11-04-2016 without track changes.

L. 15: Interdependencies and feedbacks between what? Please clarify.
between land use and water quality. We rephrased.

L. 27: This statement seems to be contradicted by L. 31 – 34. Rewording might help to avoid the confusion for a reader.
We clarified on L27 that it was median visual water clarity. L31 refers to temporal changes.

L. 31 – 34: Where do I find this information in the result section?
Table 6 and L422.

L. 70: cause-effect relationships between what?
We added “… between land use and water quality”.

L. 75 – 77: One can easily argue against this statement because in small catchments the actual transfer may be dependent on very site-specific conditions affecting connectivity, which are difficult to incorporate into existing model approaches. I suggest to tone down the statement or to provide references that actually support your statement.
We removed the word ‘small’ and added ‘heterogeneous’ to large catchments.

L. 264: How was this visual validation carried out? Please show results of the validation in the SI.
The methods and results for validation are detailed in de Beurs et al. (2016), which we state earlier in this paragraph. The results of this validation are in Table 4 of that article, so no need to reproduce here. We feel the term ‘visual validation’ of disturbance against high-resolution

imagery is self-explanatory. We looked at the image to see if the ground was disturbed (i.e. no vegetation).

L. 282: These trends were flow corrected?
The trends were calculated on flow-normalized water quality data. We added this clarification.

L. 300 – 301: Skip this reference – that a 1% change per year results in a > 10% change in a decade is simple maths.
Reference deleted.

L. 313 – 315: These details can be skipped for the sake of brevity (unless these catchments have a particular relevance which is not reported in the manuscript). For the general readers these abbreviations are just meaningless. This is of course different for people managing the specific areas. However, this paper is written for a general audience and not for local authorities.
We removed the catchment identifiers.

L. 328 – 341: This very descriptive part has to be shortened considerably.
We removed the catchment identifiers and other nonessential information, but most of the paragraph needs to stay because it characterizes the coverage of land use of our study area, which the reader needs to know in order to understand the extent of land use intensity. This is why we distinguish between intensively-managed grasslands and grasslands not intensively managed. Likewise, we distinguish between non-plantation forests and the intensively-managed plantation forests. We revised the paragraph to make this clear. Further, it is important to characterize the minimal coverages of the other land uses at the end so that the reader understands that urban, cropland, water/wetlands, and barren/other land uses have a relatively minor influence on water quality compared to the agricultural uses.

L. 576 –604: What is the novelty here? This very descriptive part has to be shortened considerably.
We revised the beginning of this section to relate explicitly to land use intensity. We then condensed these two paragraphs down to one, much shorter paragraph.

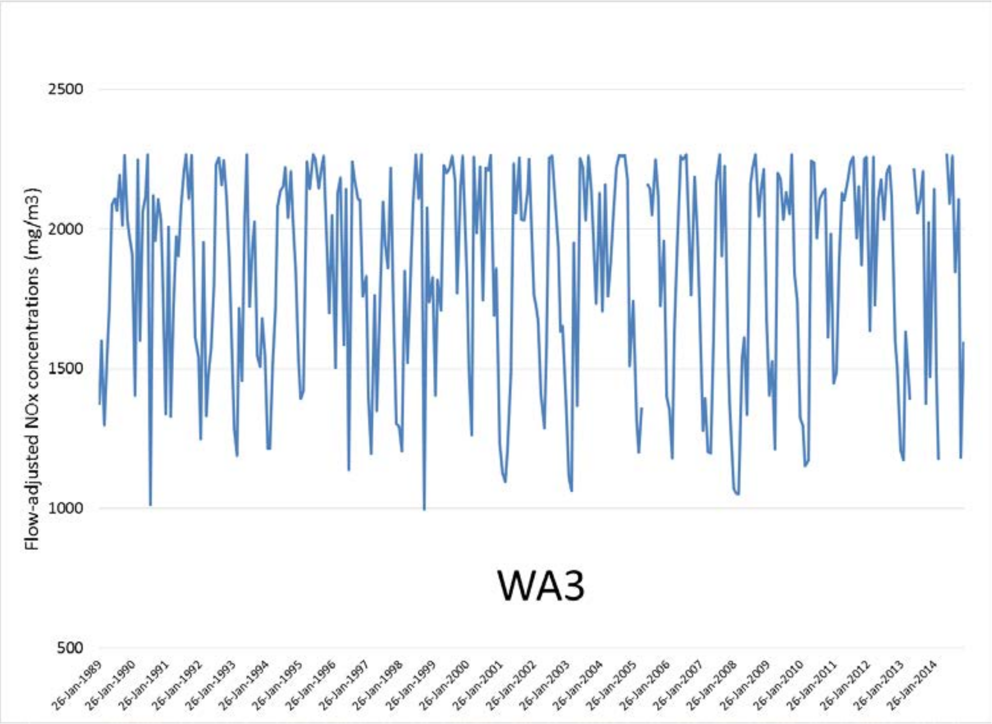
L. 854: Where can the results be seen?
These results are reported in the 3rd paragraph of section 4.3.

L. 861: You provide a reference here – so what is actually novel here. Skip was simply represents a repetition of previous findings.
We removed this detailed example, only keeping the reference that documents this process.

L. 881 – 882: Where are the data? Why is this not yet presented in the result section? Or did I miss it?
We added a reference to Supplement Tables 3 & 4, but this result is presented at the end of section 4.3 (L390).

L. 891 – 893: This argument is not convincing. What shall be the actual mechanism that prevents a high concentration to increase further?

We looked back over these data and found that the reason was “because of the extreme monthly variability in river nitrogen concentrations, possibly due to livestock rotations, fertilizer applications, and precipitation events.” We revised this sentence accordingly. I have also pasted the plot below.



L. 897 – 907: This part distracts from the main story. Skip.
L. 909 – 918: Again, this explanation of outliers distracts from the main story. Skip.
This paragraph is part of our main story, that areal coverage alone does not explain water quality. Hence our finding: “Our high temporal-resolution analyses of disturbance showed that even though this catchment is mostly indigenous forest, intense disturbances on small proportions of developed land can have a considerable impact on water quality.” Disturbance is one of our metrics of land use intensity, and this paragraph provides key examples why this disturbance metric is useful and why land use intensity is a better predictor of water quality in some cases. Also note that we did shorten this paragraph in the previous revision.

L. 919 – 934: Shorten.
We shortened this paragraph some.

Reviewer #1
Specific suggestions
L17-18 SRA '...land use intensity, defined here as the inputs of fertilizer and livestock density, and land disturbance via vegetation removal, is a better predictor of water quality impact.'
We kept our original wording because this suggested wording makes it sound like land disturbance is separate from land use intensity.

L23-26 SRA ' We analyzed spatial and temporal changes in livestock density and bare soil at the catchment-scale, as well as fertilizer inputs at the national scale.'

We feel it is necessary here to specify what causes the land disturbance (i.e. grazing and forest harvesting). Just saying bare soil could imply desert, barren land, or cultivated crops.

L28 SRA '...for four nutrient variables (a,b,c,d), however, ...'
Nutrient variables added as suggested.

L31-34 I expected to read here an explanation of why high producing pastures were positively related to water clarity. The reasoning is here but is presented as a separate finding rather than an explanation of the finding presented in L27. Please consider rephrasing.
The statement in L27 is a spatial comparison; whereas, L31 is a temporal comparison. These are two separate analyses. Hopefully our addition of 'median visual water clarity' clears this up.

L38 Please quantify 'some' as a percentage or proportion.
This would require several sentences given that we would have to address five different variables, and rivers that improved in TN did not necessarily improve in TP, or clarity, and so on. Because of the reviewers' insistence that we shorten the ms, we did not expand this sentence to reflect proportions of rivers that improved for all five variables.

L36 So is increased cattle density the cause of both improved water clarity and increased NOX?
Now we see where part of the confusion arose in the comment before last. To clear up this confusion, we added that the relationship is inverse: "median visual water clarity was best predicted inversely by …"

L38 Please quantify 'some' as a percentage or proportion. Re 'nutrients' is this P and N or just one of these nutrients? Please be specific.
As mentioned above, this would require several sentences given that we would have to address five different variables, and rivers that improved in TN did not necessarily improve in TP, or clarity, and so on. Because of the reviewers' insistence that we shorten the ms, we did not elaborate here.

L63 SRA '...pollution from fine sediments, nutrients...'
Revised as suggested. Note that this is one of the sentences we shortened.

L92-93 Consider the wording I suggest for the Abstract
We kept our original wording because this suggested wording makes it sound like land disturbance is separate from land use intensity.

L94 Suggest delete 'areal coverage' and replace with 'land use alone', because you look at areal coverage of land use intensity over time.
Revised as suggested.

L96-97 Reason 1 holds for land use alone also, so I suggest the added complexity of studying land use intensity effects is just reason 2.
These reasons were described in the Kuemmerle and Erb references provided. For one example that justifies reason 1, think about the land use of pasture. The relationship between pasture and landscape variables such as soil type is relatively straightforward; however, the interactions

among different livestock densities (i.e. land use intensity), pasture, and soil type is more complex and depends on other interacting variables. The key word in reason 1 is ‘multidimensional;’ think of land use intensity as adding another dimension, and thus another level of complexity/uncertainty.

L100 Please add a reason for 'decades pasture area has decreased' (eg due to conversion to ?) and specify which livestock have increased in density.
Both of these details are results from our analyses and thus presented in the Results section. We are only introducing the concept here.

L106-07 I expect that in some cases, such as conversion from sheep to dairy cattle pasture production, that land use change and land use intensity change are correlated. So some of these other analyses probably have addressed land-use intensity change if not directly, by proxy. Please comment.
These previous studies only looked at areal coverage of pasture (or high-producing grasslands); they did not look at changes in cattle vs sheep like we did. This is one of the reasons our study is novel.

L110 'one of the highest rates' needs a reference, or rephrasing to 'a high rate'
We added a reference, the same one we use in the Conclusions to make the same point.

L114 SRA 'variables that extend over'
Revised as suggested.

L118 re 'specifically livestock density and land disturbance'- and not fertiliser inputs as described earlier?
This statements refers to analyses of the 77 catchments. Fertilizer inputs were only assesses at the national level.

L125 catchment scales are appropriate scales for some levels of management, but not others. Field- or stream reach- scale management is appropriate for managing catchment scale outcomes in many cases. Please consider rephrasing.
We shortened this sentence and revised accordingly.

L206 Re 'intensity, and disturbance data' Earlier disturbance was defined as a sub-category of land use intensity, so please rephrase this subheading.
Revised.

L229-230 I don’t follow why bare soil would be a proxy for high-producing grasslands. see below
L235 How does stock unit density relate to livestock impact on land disturbance and/or bare soil? THis seems out of place because this section describes how livestock density was calculated and the following paragraph describes how land disturbance was calculated for various land uses. Correctly in my view, SUD doesn't appear to be used to calculate land disturbance. Please consider deleting '..on land disturbance' or describe how SUD was linked to land disturbance, including the assumptions and basis for assumptions that were used to correlate

stock density with bare soil.
We deleted '…on land disturbance' as suggested.

RE L240 How does the dataset of Ausseil for 2011 differ from that of StatsNZ and why was the Ausseil data needed? Please clarify
The Ausseil data has 1-ha resolution, which allows us to do spatial comparisons. The StatsNZ data is district-level data (which does allow precise spatial comparisons), but because it covers multiple years, it allows us to do temporal comparisons. To avoid confusion (on L245), we changed 'stock units per hectare' to 'stock unit densities.'

L243 I suggest 'intensity' rather than 'impacts' here.
Changed as suggested.

L328 To what time period do the subsequently reported land use extents refer - an average from 1990 to 2012?
In the methods (section 3.3), we have clarified that it is for the midpoint year of 2001. We also added in the 2nd sentence here that these coverages refer to the year 2001.

L365 SRA 'little over the period 1990-2012'
Revised as suggested.

L674-675 Can you provide an exemplar reference for this finding? To my knowledge, export of DRP to rivers in high Pret soils is usually driven by the tendency for runoff which is likely to be low in these free-draining allophanic soils. Other mechanisms for DRP transport to rivers in high Pret soils may be via preferential flow pathways (natural or artificial) or due to mobilisation of less readily fixed organic P forms and subsequent mineralisation into DRP at or near the point of delivery to the river.
It is common knowledge that "soils with high P_{ret} require more P-fertilizer." And it is intuitive that the more P-fertilizer added to soils, the higher the DRP export to rivers through various pathways, as you mention here. And yes, there are both natural and artificial flow pathways in these intensively managed pastures, particularly the drainage canals. Thus, we have not added a reference for this intuitive logic.

Reviewer #2
Former Line 667: the correlation of 0.45 is still not high what also means it is not relatively high. Please correct this
This statement is no longer in the revised ms.

Please consider the editors comment on former lines 417-429 on shortening the manuscript as suggested
We shortened this paragraph.

Please shorten also the line 520-547 as suggested by the editor.
These suggestions on shortening the manuscript are mandatory!
We condensed these two paragraphs down to one, much shorter paragraph.

River water quality changes in New Zealand over 26 years (1989 – 2014): Response to land use intensity

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Abstract

Relationships between ~~L~~land use and~~-~~ water quality ~~relationships~~ are complex with interdependencies, feedbacks, and legacy effects. Most river water quality studies have assessed catchment land use as areal coverage, but here, we hypothesize and test whether land use *intensity* – the inputs (fertilizer, livestock) and activities (vegetation removal) of land use – is a better predictor of environmental impact. We use New Zealand (NZ) as a case study because it has had one of the highest rates of agricultural land intensification globally over recent decades. We interpreted water quality state and trends for the 26 years from 1989 to 2014 in the National Rivers Water Quality Network (NRWQN) –consisting of 77 sites on 35 mostly large river systems~~ with an aggregate catchment amounting to half of NZ's land area~~. To characterize land use intensity, we analyzed spatial and temporal changes in livestock density and land disturbance (i.e. bare soil resulting from vegetation loss by either grazing or forest harvesting) at the catchment-scale, as well as fertilizer inputs at the national scale. Using simple multivariate statistical analyses across the 77 catchments, we found that median visual water clarity was best predicted inversely by areal coverage of intensively managed~~high-producing~~ pastures. The primary predictor for all four nutrient variables *(TN, NO_x, TP, DRP)*, however, was cattle density, with plantation forest coverage as the secondary predictor variable. While land disturbance was not itself a strong predictor of water quality, it did help explain outliers of land use-water quality relationships. From 1990 to 2014, visual clarity significantly improved in 34/77 catchments, which we attribute mainly to increased dairy cattle exclusion from rivers (despite dairy expansion) and the considerable decrease in sheep numbers across the NZ landscape, from 58 million sheep in 1990 to 31 million in 2012. Nutrient concentrations increased in many of NZ's rivers with dissolved oxidized nitrogen significantly increasing in 27/77 catchments, which we largely attribute to increased cattle density and legacy nutrients that have built up on intensively managed ~~high-producing~~ grasslands and plantation forests since the 1950s and are slowly leaking to the rivers. Despite recent improvements in water quality for some NZ rivers, these legacy nutrients and continued agricultural intensification are expected to pose broad-scale environmental problems for decades to come.

1. Introduction

River water quality reflects multiple activities and processes within its catchment, including geomorphic processes, vegetation characteristics, climate, and anthropogenic land uses (Brierley, 2010). Relationships between water quality and these catchment characteristics are not straightforward because all of these factors interact over both space and time. For example, if intensive livestock grazing occurs on steep slopes, surface runoff and consequently river turbidity is expected to be greater than if grazing occurs on flatter areas. Or if fertilizers are heavily applied to sandy soils with high drainage density, rivers will likely become eutrophied over a period of decades due to legacy nutrients slowly leaking to the rivers through groundwater (McDowell et al., 2008). The influence of land use on water quality has also been shown to vary among different climates (Larned et al., 2004). With all of the various types of intensive land uses that have occurred across diverse landscapes over hundreds of years, rivers with degraded water quality are now widespread.

Historically, water quality in rivers was managed to meet minimally acceptable standards or maximum pollutant load limits (Baron et al., 2002; Boesch, 2002; Howard-Williams et al., 2010). However, in the last decade, a greater emphasis has been placed on maximizing the ecosystem services provided by healthy rivers, which is driving efforts to further improve water quality (Brauman et al., 2007; Davies-Colley, 2013). Early efforts in developed countries to improve water quality focused on point-source pollution, particularly wastewater discharges from factories and treatment plants (Campbell et al., 2004). While the broad-scale reduction in point-source pollution elevated many water quality variables above minimal standards, most rivers globally still have water quality impairments due to diffuse pollution ~~–~~from fine sediments, nutrients, ~~pathogens, toxicants, salts,~~ and other contaminants ~~that are delivered from unknown or many indistinguishable sources across the catchment~~ (Vorosmarty et al., 2010). Although considerable effort has been directed at monitoring and reducing diffuse pollution with some success, the legacy of pollutants from various land uses remains (Boesch, 2002; Kronvang et al., 2008; Zobrist and Reichert, 2006). Agricultural land uses are by far the greatest contributors of diffuse pollution~~,~~ globally (Foley et al., 2005; Vitousek et al., 1997); however, the 'intangible' sources of diffuse pollution make it difficult to assign cause-and-effect relationships between land use and water quality (Campbell et al. 2004).

Many studies have used theoretical or numerical models to examine relationships between land use and water quality because of the lack of consistent water quality monitoring over long periods (bracketing land use change). While modelling approaches can be useful for ~~small~~ catchments where much is known about its landscape, modelling may not work well for large, heterogeneous~~r~~ catchments because land-water relationships are complex with interdependencies, feedbacks, and legacy effects. Empirical studies can shed light on some of these complexities, but they are only useful for their particular catchments and may have limited generality or transferability. Comparisons of many diverse catchments is probably most useful to advance understanding of broad-scale land-water relationships (Zobrist and Reichert, 2006).

One of the most comprehensive empirical multi-catchment studies to date on land use-water quality relationships has been Varanka and Luoto's (2012) study of 32 boreal rivers in Finland. They analyzed five water quality variables over ten years as a function of a suite of physiographic, climate, and land use variables. A similar study was conducted on many of the same rivers in Finland, but with a more sophisticated temporal analysis (Ekholm et al., 2015). ~~And several other studies have used this same river water quality dataset to investigate environmental drivers.~~ In a study of 11 Swiss watersheds, Zobrist and Reichert (2006) analyzed export coefficients of six water quality variables from biweekly, flow proportional, composite samples over a 24-year period within the context of land use.

All of these studies, and most catchment land use studies, assessed land use (or land use change) as areal coverage. However, land use *intensity* – the inputs (e.g. fertilizer, livestock) and activities (e.g. vegetation removal) of land use – could be a better predictor of environmental impact for being a more direct measure of impact than ~~areal coverage~~land use alone (Blüthgen et al., 2012; Ramankutty et al., 2006). Unfortunately, our understanding of the patterns, processes, and impacts of land use intensity is inadequate because of (1) its complex, multidimensional interactions with other landscape variables, and (2) the lack of appropriate datasets across broad spatiotemporal scales (Kuemmerle et al., 2013; Erb et al., 2016). New Zealand (NZ) provides a valuable test-bed for the patterns, processes, and impacts of land use intensity because over the past three decades pasture area has decreased but livestock densities and fertilizer inputs have increased (MacLeod and Moller, 2006; StatsNZ, 2015). Like Finland and Switzerland, NZ has an extensive long-term river water quality monitoring network, which has allowed many studies on river water quality state and trends (Smith et al., 1996, 1997; Scarsbrook et al., 2003; Scarsbrook, 2006; Ballantine and Davies-Colley, 2014) and effects of land use areal coverage (Davies-Colley, 2013; Larned et al., 2004, 2016). However, this dataset has not been assessed as regards changes in land use intensity that have occurred over the same period.

Here, we investigate long-term relationships among land use intensity, geomorphic processes, and river water quality in NZ − which provides a particularly valuable case study because: (1) it has had one of the highest rates of agricultural land intensification over recent decades (OECD/FAO, 2015) and thus serves as a potential indicator for countries that are also increasing agricultural intensity; (2) it has a long, consistent, and comprehensive national water quality dataset; and (3) it is physiographically-diverse. We examined monthly data for a suite of water quality variables that extend over a 26-year period for 77 diverse catchments. We then compared these states and trends of river water quality to landscape data that characterized the catchments' geomorphology, soil properties, and hydro-climatology; as well as temporal changes in land use areal coverage and land use intensity, specifically livestock density and land disturbance, defined here as bare soil resulting from vegetation loss. Altogether, these analyses reveal coincident spatiotemporal patterns in land use intensity and water quality over a quarter of a century. Most of our analyses were performed at the catchment scale which integrates the spatiotemporal changes that are reflected in our water quality measurements~~,~~ and is the most appropriate scale to manage~~analyze~~ diffuse pollution~~, and is the most appropriate spatial management unit~~ (Howard-Williams et al., 2010).

2. Study area

New Zealand ~~(*Aotearoa*, “Land of the long white cloud” in the language of indigenous *Maori* people)~~ is a small island nation (~268,000 km^2) located between the South Pacific Ocean to the east and the Tasman Sea to the west. Its two main islands, ~~(~~North Island and South Island,~~)~~ are located between 34° and 47° S latitude. Being located on the active boundary between the Australian and Pacific Plates, NZ’s geology and geomorphology are very diverse, including active volcanoes, karst regions, a range of high fold mountains (the Southern Alps), large coastal plains, and rolling hills across both hard- and soft-rocks. Being stretched latitudinally, with nowhere more than about 150 km from the sea, between two major ocean waters combined with its topographic variability, NZ also has a diverse climate with regional extremes, including sub-tropical in the far north, temperate in the central North Island, extremely wet on the western side of the Southern Alps (up to 10 m annually), and semi-arid in the rain shadow to the east of the Southern Alps.

New Zealand is the last major habitable landmass to be settled by humans. Eastern Polynesians first arrived around 1300 AD (Wilmshurst et al., 2008). Europeans first arrived in the late-1700s, but large-scale settlement did not begin until the 1840s. Broad-scale agriculture spread shortly after and has been intensifying since. While we address land use changes at the national scale in this study, our water quality analyses focus on 77 diverse catchments across NZ (Fig. 1)~~, which cumulatively cover about half of NZ's land area~~.

3. Methods

3.1. Water quality data

Water quality data was obtained from NZ's National Rivers Water Quality Network (NRWQN), which is operated and maintained by the National Institute of Water & Atmospheric Research (NIWA). This network represents one of the world's most comprehensive river water quality datasets: thirteen water quality and two biomonitoring variables have been measured monthly (via in situ measurements and grab samples), with supporting flow estimation, from 1989-2014 at 77 sites whose catchments cumulatively drain approximately half of N~~ew~~ Z~~ealand~~'s land surface (Davies-Colley et al., 2011). Further, this dataset has been operationally stable throughout its history, which allows us to calculate trends over this period. For this study, we focused on eleven water quality variables and their coincident flow (Table 1). We did not analyze ammoniacal nitrogen (NH_4) because early NH_4 samples were biased high by laboratory contamination (Davies-Colley et al., 2011).

All water quality variables, except water temperature (T_w), were flow-normalized (for each site separately) in JMP® Pro (v 11.2.1) with local polynomial regression (LOESS) using a quadratic fit, a tri-cube weighting function, a smoothing window (alpha) of 0.67, and a four-pass robustness to minimize the weights of outliers (Cleveland and Devlin, 1988); where, flow-adjusted value = raw value – LOESS value + median value. With LOESS, there is no assumption about the water quality variable's relationship with flow. For example, although visual clarity usually decreases systematically with increasing flow (Smith et al., 1997), algae blooms at low flows can sometimes reduce clarity. LOESS also allowed us to examine relative water quality changes over long periods.

We assessed water quality states and trends with ANZECC (2000) guidelines, which are the 20th-percentile of the first decade of the NRWQN record for ‘reference’ sites. These guidelines are ‘trigger values’ that when exceeded trigger a management response to protect ecosystem health (Hart et al., 1999). Although these ‘trigger values’ are not effects-based standards (which would be difficult to define for the wide variety of NZ ecosystems), they do provide a useful reference for comparing water quality states and trends. Upland and lowland catchments, distinguished by the 150 m elevation threshold, have different guidelines that take into account that lowland rivers are typically more turbid and nutrient-rich.

3.2. Physiographic data

Water quality metrics and trends were compared to a suite of landscape variables (Table 2). Catchment morphometrics (area, slope, ruggedness) were obtained from a 30-m digital elevation model (DEM) that we rescaled (in order to align with other gridded spatial datasets) from the 25-m DEM produced by Landcare Research (LCR). This 25-m DEM was interpolated from 20-m contours of the national TOPOBASE digital topographic dataset supplied by Land Information N~~ew ~~Z~~ealand~~ (LINZ; scale: 1:50,000). Catchment area (A) is the drainage area (in km^2) above the NRWQN station, derived using Arc Hydro tools in ArcGIS 9.3.1 in combination with the River Environment Classification (REC, v2.0), the national hydrography dataset derived from a 30-m hydrologically correct DEM (Snelder et al., 2010). Mean catchment slope (S_c) was derived from the same software package, using a 3x3 cell window. We defined ruggedness (R_r)

as the standard deviation of the 30-m slope grid for each catchment (*sensu* Grohmann et al., 2011). Drainage density (D_d) was calculated from the ratio of the total length of REC streams to catchment area (in km/km^2).

Soils data was obtained from the 1:50,000 Fundamental Soils Layers (FSL), which is maintained by LCR~~andcare Research~~. Methods and data descriptions for this soils database are described in Webb and Wilson (1995) and Newsome et al. (2008). Catchment-scale soil variables (mean value across catchment) that we included in our analysis for being expected to be related to water quality were: soil depth (Z_s), percent of catchment dominated by silty and clayey surface soils (*SC%*), soil pH (pH_s), cation exchange capacity (*CEC*), organic matter percentage (*OM%*), and phosphate retention (P_{ret}). Phosphate retention is a measure (in %) of the amount of phosphate that is removed from solution by the soil via sorption (Saunders, 1965). Thus, soils with high P_{ret} have low P-availability for plant growth.

Median annual precipitation (*MAP*), median annual temperature (*MAT*), and median annual sunshine (*MAS*) averaged across each catchment was obtained from NIWA's National Climate Database, which contained 5-km gridded daily weather data (Tait and Turner, 2005). Our values for these three variables represent the median annual precipitation (total mm/y), temperature (mean °C), and sunshine (hours/y) for the period 1981-2010. Relative water storage (*RWS*) was calculated as the proportion of the annual catchment water yield (i.e. total volume of water leaving the catchment in a year) stored in lakes and reservoirs. Reservoir/lake storage was obtained from the Freshwater Ecosystems of N~~ew ~~Z~~ealand~~ (FENZ) Database, described in Snelder (2006). The last hydro-climatological variable we included in our analyses was the median discharge (Q_{50}), which was calculated from the NRWQN 'flow stamping' at times of water quality sampling from 1989-2014.

3.3. Land use ~~areal coverage,~~ and intensity~~, and disturbance~~ data

There are two national land use datasets for N~~ew~~ Z~~ealand~~. The Land-Use and Carbon Analysis System (LUCAS) was developed by the NZ Ministry for the Environment (MfE, 2012) for reporting and accounting of carbon fluxes and greenhouse gas emissions, as required by the United Nations Framework on Climate Change and the Kyoto Protocol. Accordingly, LUCAS uses 1990 as its reference year and maps land use in 12 classes for 2008 and 2012. The Land Cover Database (LCDB) was developed by ~~Landcare Research (~~LCR~~)~~, with contributions from MfE, Department of Conservation~~ (DOC)~~, Ministry for Primary Industries~~ (MPI)~~, and Regional Councils (LCR, 2015). LCDB contains 35 land use classes for 1996, 2001, 2008, and 2012. Both datasets use a minimum mapping area of 1 ha~~ectare~~, and use many of the same data and methods to map land use. There are however, some key differences in their class designations and classifications that are important to our analyses: (1) LUCAS includes Manuka/Kanuka as forest, whereas LCDB designates Manuka/Kanuka as shrub; (2) LUCAS lumps all post-1989 forests into one class, whereas LCDB differentiates between indigenous and plantation forests; (3) LUCAS uses a conservative approach to map~~ping~~ high-producing grasslands, whereas LCDB uses phenological information to provide more accurate estimations of high-producing grassland. Because of our focus on (water quality-impacting) plantation forests and high-producing grasslands, we used the LCDB (v4.1) for the midpoint year 2001 for our spatial and statistical analyses. We used LUCAS only to quantify long-term changes from 1990 to 2012, before the LCDB was initiated in 1996. Table 3 describes the land use classes we used in this research, which classes are included from both datasets, and the national comparison between LUCAS and LCDB for 2012.

There are numerous metrics for land use intensity (Erb et al., 2013). At the catchment-scale, we used livestock density as a metric for all grasslands; and we used land disturbance, defined here as bare soil resulting from vegetation loss, as a metric for high-producing grasslands and plantation forests. We also used national-scale annual fertilizer data (1989-2014) from StatsNZ (2015) to compare long-term trends of river nutrient concentrations to nutrient inputs. Livestock numbers for dairy cattle, beef cattle, sheep, and deer (at 1 ha resolution) for each catchment were derived from maps provided by Ausseil et al. (2013), which is representative for the year 2011. To assess total livestock impact~~ on land disturbance~~, we multiplied each livestock type by its AgriBase stock unit (SU) coefficient: sheep = 0.95 SU, deer = 1.9 SU, beef cattle = 5.3 SU, and dairy cattle = 6.65 SU (Woods et al., 2006). The total SU for each catchment was then normalized by total catchment area, expressed as stock unit density (SUD) in SU/ha.

Changes in SUD from 1990 to 2012 ($SUD_{2012-1990}$) were assessed using district-level data from StatsNZ (2015) on total numbers of sheep, deer, beef cattle, and dairy cattle. These livestock numbers were then aggregated for each catchment and multiplied by their respective SU coefficient. Stock unit densities ~~per hectare~~ were then compared between 1990 and 2012 to assess change in livestock ~~impacts~~ intensity in each catchment. For Whakatane and Kawerau Districts, 1993 was used because 1990 data was unavailable.

Land disturbance (i.e. bare soil resulting from vegetation loss) was quantified for all high-producing grasslands (D_{HG}) and plantation forests (D_{PF}), as well as the whole catchment (D_C) for the period 2000 - 2013. The methods for calculating and validating disturbance are described in de Beurs et al. (2016). Briefly, MODIS BRDF corrected reflectance data (MCD43A4) at 463 m spatial resolution and eight day temporal resolution was used to calculate Tasseled Cap brightness, greenness and wetness based on the coefficients following Lobser and

Cohen (2007). These indices consist of linear combinations of all seven MODIS reflectance bands to represent general image brightness which is comparable to albedo, image greenness which is comparable to the better known vegetation indices such as NDVI and EVI, and image wetness which is linked to the amount of water captured in the vegetation, most comparable to normalized difference water indices. Missing pixels were ignored. We then calculated the mean and standard deviation of each tasseled cap index for each combination of land cover class (LCR, 2015) and climatic region for each 8-day time period. We then used these measures to standardize the calculated tasseled cap indices. To determine how disturbed each pixel was at any point in time, we then calculated the forest and grassland disturbances. The forest disturbance index is calculated as the standardized brightness minus the standardized greenness and wetness. The idea is that disturbed forests appear brighter and less green and less wet than undisturbed forests. The grassland index is the negative sum of all indices, indicating that disturbed grasslands appear darker, less green and less wet than undisturbed grasslands. MODIS disturbance data were visually validated against 7500 random pixels from Landsat imagery and corresponding 15 high resolution Orbview-3 and Ikonos images. The overall accuracy of the disturbance index based on Landsat data was 98%.

3.4. Statistical methods

We used nonparametric Spearman rank correlation coefficients (r_s) to look at relationships between variables because many of the relationships were curvilinear. Statistical significance was taken to be an alpha of 0.05. Bivariate comparisons between all variables (Tables 1-3) were performed to explore for associations and identify correlated variables before later multivariate analyses. Median values (from the 26-y monthly time-series) for water quality variables at each site were used when compared to physiographic and land use variables of their corresponding catchment. Stepwise regression was then used to rank-order the relative contributions of multiple landscape variables associated with each major water quality variable. Stepwise regression was used because it accounts for correlations among the independent landscape variables. The order of variables in the stepwise regression model and the sign of their coefficient (proportional [+] vs. inverse [-]) provides an objective measure of the contribution of each landscape variable to river water quality. The level of entry into the model was set to p = 0.05. All the above statistical analyses were performed in JMP® Pro (v 11.2.1).

Temporal trends in flow-normalized water quality (1989 – 2014) and disturbance (2000 – 2013) data were assessed with the ~~s~~Seasonal Kendall (SK) test which was corrected for temporal autocorrelation using the rkt R package; missing values were ignored. We also calculated the S~~easonal ~~K~~endall~~ slope estimators (SKSE) using the same R package. Because some NRWQN sites had multiple measurements in some months, a few records (no more than five) were removed from each site in order to ensure 12 monthly values for each year for the SKSE test. There were also occasional missing values for some variables throughout the time-series, particularly in the early years. Of particular note, there were no *TN* values for 1994 as a result of contamination by leaking ammonia refrigerant during storage of frozen subsamples. HV1 did not have data for 18 months from 2012-2014.

In order to make trend comparisons among sites and derive an estimate of percent change per year, we normalized SKSE values by dividing them by the raw data median to give the relative SKSE (RSKSE) in percent change per year (Smith et al., 1996). Given that water temperature (T_w) uses an arbitrary scale in °C, we only report SKSE values for this variable. We also used the trend categories of Scarsbrook (2006): (1) no significant trend – the null hypothesis for the S~~easonal ~~K~~endall~~ test was not rejected ($p > 0.05$); (2) significant increase/decrease – the null hypothesis for the S~~easonal ~~K~~endall~~ test was rejected ($p < 0.05$); and (3) ‘meaningful’ increase/decrease – the trend was significant and the magnitude of the trend (RSKSE) was greater than 1% per year. ~~According to Ballantine and Davies-Colley (2014), a ~~A 1% change per year translates to slightly more than 10% change per decade (due to compounding), a rate of change that is easily detectable and observable.

4. Results

4.1. Physiographic characteristics

The 77 NRWQN catchments were physiographically diverse in terms of morphometric, soil, and hydro-climatological variables (Table 4; Supplement Table 1). Most notable with regards to its direct influence on runoff and water quality was median annual precipitation (*MAP*), which ranged from 533 to 7,044 mm/y. When combined with the wide range of catchment areas (*A*), median discharge (Q_{50}) varied over three orders of magnitude, from 0.4 to 515 m^3/s, and annual water yield from 103 to 3,475 mm/y. In terms of soil, about a quarter of the catchments had very sandy surface soils ($SC\% < 10$) and a quarter had fine-textured soils ($SC\% > 70$). Phosphate retention (P_{ret}), an important variable for fertilizer management and consequently water quality, was particularly high (>57%; 10th percentile) for seven catchments in the central North Island~~ HM2, HM5, HM6, WA1, WA2, WA3, and WN5~~.

Several physiographic variables (Table 2) displayed strong latitudinal trends from North to South ~~-~~and many were strongly correlated ($p < 0.001$; Supplement Fig. 1). In consideration of these relationships and perceived importance for water quality (*sensu* Varanka and Luoto, 2012), we used the following subset of minimally correlated physiographic variables for subsequent multivariate analyses: catchment slope (S_c), silt-clay percentage ($SC\%$), phosphate retention (P_{ret}), and median flow (Q_{50}).

4.2. Land use areal coverage and temporal changes

Land use in NZ, like physiography, varied widely; and our 77 catchments captured this diversity (Fig. 1; Supplement Table 2). In 2001, ~~Thirteen~~13 catchments were dominated ~~(>50%)~~ by non-plantation forests (*NF*), while 3 catchments were dominated by intensively managed plantation forests (*PF*)~~, with one (WN2) containing more than 94%~~. Thirteen ~~other~~ catchments were dominated by shrub/grassland (*SG*) that was not intensively managed. The most dominant land use was grasslands that were intensively managed (~~hereafter~~ high-producing grasslands; *HG*), covering the majority of the area for 31 catchments. ~~Together, these three land uses made up 84% of the catchments' areas. Plantation forest (*PF*) was the majority land use for three catchments (RO3, RO5, RO2).~~ Open water (*OW*) was the majority land use for only one catchment ~~(RO1)~~ and relatively high (>10%) for two others ~~(RO6, DN10)~~. Barren/other (*BO*), which was largely bare rock, was relatively high (>10%) for 13 mountainous catchments. Urban (*UR*) coverage rarely exceeded 1%, with only one catchment greater than 2% ~~(WN1)~~. Annual cropland (*AC*) exceeded 1% in 11 catchments, but never exceeded 8%. Vegetated wetland (*VW*) and perennial cropland (*PC*) were minimal in all catchments, each rarely exceeding 1%.

In general, *NF*, *SG* and *BO* areas dominated mountainous catchments with high S_c and low Z_s; while *HG* dominated most lowland catchments with low S_c, high Z_s, and high pH_s. Like *HG*, *PF* mostly occurred on flat areas (r_s = -0.48 with S_c) with thick soils (0.35 with Z_s) that were less acidic (0.31 with pH_s). Given the relative dominance of catchment land use, relationships with physiographic variables, and potential effects on water quality in NZ rivers

(Davies-Colley, 2013; Howard-Williams et al., 2010), the land use variables used for subsequent multivariate analyses were *NF*, *SG*, *HG*, *PF*, and *OW*.

Land use areal coverage did not change much from 1990 to 2012 across NZ (Fig. 2) or in many catchments (Supplement Table 2). The greatest change was a 13.4% increase in *PF* in GS1, which was almost entirely accounted for by a 13% decrease in *SG*. Thirteen other catchments experienced small increases (3.0 - 6.6%) in *PF*, accounted for by decreases in *SG* or *HG* or both. HM3 and HM4 had the greatest increases in *HG* at 3.4% and 2.0%, respectively. High-producing grasslands (*HG*) for the other 75 catchments remained virtually unchanged (< 0.4%) or decreased. WH3 had the greatest decrease in *HG* at -4.8%. Land use areal coverage change in other catchments was negligible.

4.3. Land use intensity and temporal changes

Changes in total stock unit density between 1990 and 2012 ($SUD_{2012\text{-}1990}$) were also minor with only two catchments ~~(AK1 and AK2: both -5.1 SU/ha owing to urban fringe expansion)~~ changing more than 1.6 SU/ha over this period (Supplement Table 3). Temporal changes in $SUD_{2012\text{-}1990}$ for 56 of the 77 catchments were within the range of -1.0 to 1.0 SU/ha. Although land use areal coverage and total livestock densities changed little over the period 1990-2012, livestock *types* changed considerably for many catchments (Supplement Table 3) and across NZ (Fig. 2). The general pattern was dairy cattle replacing sheep. The number of dairy cattle from 1990 to 2012 increased in 72 catchments, with a mean increase of 0.6 SU/ha for all catchments; while the number of sheep decreased in all 77 catchments (mean = -0.9 SU/ha). Deer and beef cattle numbers changed little: 0.0 and -0.2 SU/ha, respectively.

When 2011 livestock densities were compared with physiographic variables, the strongest relationships were found with combined *SUD* of dairy and beef cattle (hereafter SUD_{cattle}; Supplement Fig. 2). SUD_{cattle} decreased strongly with increasing slope, S_c (r_s = -0.79), but increased with Z_s (0.43), pH_s (0.32), and P_{ret} (0.27). SUD_{cattle} also increased with *MAT* (0.68) and *MAS* (0.42), but decreased with *MAP* (-0.34). Thus, highest cattle densities were found in catchments such as WA3 (with the highest SUD_{cattle} at 15.7 SU/ha) that were relatively flat, warm, sunny, and dry, with deep soils that had relatively high pH and high P-retention. High-producing grasslands (*HG*) had similar, but less strong, correlations with these same physiographic variables.

Catchment disturbance (D_C) varied widely over both space and time between 2000 and 2013 (Supplement Table 4). The maximum amount of D_C at one time was 35.7% for WN3 on 07-Apr-2003, almost entirely due to bare pastures. D_C exceeded 15% on six other occasions (264 days in total) in this catchment. In general, the North Island (Fig. 3) had a greater extent and intensity of disturbance than the South Island (Fig. 4). The most intense disturbances occurred as a result of plantation forest harvests, and these disturbances were on average visible for about 1.5 y up to about 4 y, with exceptions lasting more than 6 y. Indeed, D_C was strongly correlated to *PF* coverage (r_s = 0.51). The catchment with the highest median D_C (10.5%) was RO3, which had 69.8% of its catchment in *PF* and 17.7% in *HG*. Fourteen other catchments had D_C above 5%, and two-thirds of these were dominated by either *PF* or *HG*.

We also analyzed disturbance of plantation forests (D_{PF}) and high-producing grasslands (D_{HG}) separately for each catchment. For catchments with at least 21.4-km^2 (100 MODIS pixels, for the sake of statistical robustness) of plantation forest, the mean (±SD) D_{PF} (from 2000 to 2013) was 10.6 ± 5.6%. The catchments with the highest D_{PF} were those with low mean annual precipitation, MAP (r_s = -0.42). There were no significant relationships between D_{PF} and any of the other physiographic variables. For catchments with at least 21.4-km^2 of high-producing grasslands, the mean (±SD) D_{HG} was 6.0 ± 6.4%. The catchments with the highest D_{HG} were those with low mean annual sunshine (MAS; r_s = -0.25), low mean annual temperature (MAT; -0.30), high catchment slope (S_c; 0.25), and high ruggedness (R_r; 0.31). The six catchments with the highest D_{HG} (>15%) all had low phosphate retention (P_{ret}; <32%). While it is assumed that greater densities of livestock lead to greater pasture disturbance, we did not find a proportional relationship between stock unit density (SUD) and D_{HG} among catchments. In fact, the highest median D_{HG} was found for catchments with *low SUD* (r_s = -0.45). Over time however, we observed a fairly strong trend (r_s = 0.50) of lower D_{HG} with decreasing SUD ($-SUD_{2012\text{-}1990}$). In all there were seven catchments with significant or meaningful decreases in D_{HG} from 2000 to 2013 (assessed with ~~Seasonal Kendall slope;~~ SKSE), all of which had a negative $SUD_{2012\text{-}1990}$.

4.4. Water quality characteristics and trends

4.4.1. Catchment characteristics

Median monthly values of water quality variables for the 77 catchments ranged widely (Table 5; Supplement Table 5). Some rivers had exceptional water quality all around, while others had either current issues with multiple variables or worsening temporal trends (assessed with SKSE from 1989 to 2014; Table 6). Because of the dependence of water quality on flow, we first assessed temporal trends in Q. Only two catchments had significant increases in Q ~~(AX4, WH4)~~, with ~~the latter~~one also being ‘meaningful.’ Three catchments had significant decreases in Q ~~(HM3, HM5, TU2)~~ and five others also had ‘meaningful’ decreases in Q ~~(CH2, GY4, HM4, RO3, RO4)~~.

Water temperatures (T_w) were not particularly high for any of the catchments; however, 21 rivers had significant increases in T_w, possibly the signature of climate change. ~~The highest rates of T_w increase (0.04°C/y < SKSE < 0.08°C/y) were for large alpine rivers in the central South Island covered mostly by shrub/grasslands (TK3, TK4, TK6, AX3).~~ Because of its strong latitudinal trend (stronger than any land use effect), T_w was not analyzed further. Dissolved oxygen (*DO*) was close to 100% for most catchments, but was particularly low (<90%) for two catchments: one affected by peri-urban activities (AK2) and ~~RO2 which was~~one affected by discharge from a large pulp mill (RO2)~~at Kawerau, and AK2 which is on the Auckland fringe and thus affected by various peri-urban activities~~. ~~*DO* was very high (>110%) for one catchment (HV2) due to supersaturation from high periphyton in this nutrient-enriched river.~~ Temporal trends in *DO* from 1989 to 2014 were relatively minor (RSKSE < 0.5%/y), except RO2 which had a significant increase ~~(RSKSE = 0.7%/y)~~ attributable to progressive improvements in treatment of organic waste from its large pulp mill. Conductivity (*COND*) was relatively low (<115 µS/cm) for all South Island catchments and varied considerably for the North Island (54-528 µS/cm). Most catchments (52/77) experienced significant or 'meaningful' increases in *COND* from 1989 to 2014. Water pH (pH_w) was neutral to alkaline for all rivers, which have been described as calcium-sodium bicarbonate waters by Close and Davies-Colley (1990), and only displayed minor changes ~~(RSKSE < ±0.1%/y)~~ over the 26-year study period.

Median visual water clarity (*CLAR*) was exceptionally high (>5 m) for seven catchments and very low (<1 m) for 22 catchments. Since 1989, *CLAR* improved in almost half of the rivers, and worsened in 4 rivers (Table 6; Supplement Table 5). *TURB* was strongly inversely proportional to *CLAR* ($r_s = -0.97$) and generally followed opposite trends of *CLAR*. ~~However, fewer of its trends were significant and it had a disproportionally large number of 'meaningful'~~

~~increases (17 catchments compared to only 2 'meaningful' decreases in *CLAR*).~~ *CDOM* was low for most of the rivers, with only five catchments greater than 2.0 m^{-1}. Nineteen of the catchments experienced significant or 'meaningful' decreases in CDOM since 1989, possibly due to the loss of wetlands across NZ. Only one catchment had a 'meaningful' increase in *CDOM* ~~(TK3)~~.

Total nitrogen (*TN*) was relatively high (>455 mg/m^3) for almost a third of the catchments, with the vast majority (17/23) of these being lowland catchments ~~(<150 m in elevation)~~. Most of these catchments also had relatively high NO_x. Thirty-three catchments had significant or 'meaningful' increases in *TN* from 1989 to 2014, while only five had significant or 'meaningful' decreases in *TN* (Table 6). NO_x had a similar number of increasing temporal trends, but also had 'meaningful' decreases for 12 catchments. Total phosphorus (*TP*) followed a similar geographical pattern as *TN*. Eighteen of the 23 catchments with relatively high *TP* (>30 mg/m^3) were lowland catchments. Most of the catchments with relatively high *TP* (18/23) also had relatively high *DRP* (>9.5 mg/m^3). Seventeen catchments had 'meaningful' increases in *DRP*, compared to only three with 'meaningful' decreases. There was more of a balance in temporal trends of *TP*, with eight 'meaningful' increases and seven 'meaningful' decreases.

In addition to the expected correlations between *CLAR* and *TURB,* and among the nitrogen and phosphorus constituents, several other significant relationships existed among the water quality variables (Supplement Fig. 3). Taking into consideration this broad multicollinearity, we focus our multivariate analyses on several key water quality variables, particularly those that experienced the most changes from 1989 to 2014 (Table 6): *CLAR*, *TN*, NO_x, *TP*, and *DRP*.

4.5. Water quality relationships with physiography, land use, livestock density, and disturbance

Visual water clarity (*CLAR*) generally decreased with *A* (-0.37; all following parentheses in this section are r_s unless specified). Except for *TURB* (0.32), no other water quality variables had significant relationships with catchment area. Several water quality variables correlated with catchment slope (S_c), including: *TN* (-0.72), *TP* (-0.63), and *DRP* (-0.65), meaning N and P concentrations were relatively high in lowland (low slope) catchments. *DRP* (0.65) and *TP* (0.61) were directly proportional to mean annual temperature (*MAT*), but this association probably arises because the highest phosphorus values occurred mainly in lowland catchments and some of the northernmost catchments, temperature being strongly correlated with altitude and latitude. *DRP* also had a ~~(counterintuitive)~~ significant relationship with soil phosphate retention, P_{ret} (0.35). No other strong physiographic relationships emerged from our analyses.

The strongest relationships between water quality and land use areal coverage (Table 7) included high-producing grasslands (*HG*), which had strong positive relationships with several water quality variables except *CLAR* which decreased as *HG* increased. The lesser-managed shrub/grasslands (*SG*) had generally opposite relationships with water quality, but note that *SG* did not have significant relationships with *TURB* or *CLAR*. Non-plantation forest (*NF*) followed the same trends as *SG*, but had fewer significant relationships with water quality. Plantation forest (*PF*), on the other hand, followed the same trends as *HG*, with poorer water quality being associated with greater coverage of *PF*; although correlations were not as strong as *HG*. *CDOM*, *DRP*, and all N-constituents had significant negative correlations with open water (*OW*), meaning that water quality improved with greater *OW* coverage, plausibly due to entrapment of fine sediment and nutrients.

Water quality was significantly correlated with all stock unit density (SUD) metrics (Table 7; Supplement Fig. 4), except deer (SUD_{de}) which only had relatively weak relationships with *TN* and NO_x. The nutrients and CDOM had the strongest correlations with SUD_{cattle}, which includes both dairy and beef cattle. *COND*, *CLAR*, and *TURB* had the strongest (slightly) correlations with SUD_{be}. Overall, degraded water quality was strongly associated with high livestock densities, even stronger than areal coverage of *HG*~~high-producing grasslands~~.

No significant correlations between water quality and total catchment disturbance (D_C) were found; however, there were significant associations when disturbance was isolated by high-producing grasslands (D_{HG}) and plantation forest (D_{PF}; Table 7). Unexpectedly, *CLAR* and *TURB* were not correlated to D_{HG}, and surprisingly, the rest of the water quality variables had a significant *inverse* relationship with D_{HG}. Conversely, *CLAR* was the only water quality variable correlated to plantation forest disturbance, D_{PF} (r_s = -0.27). Some interesting results emerged when temporal trends in water quality (via SKSE) were assessed for catchments with high disturbance. Of the 15 catchments with D_c greater than 5%, six had 'meaningful' increases in *TURB* ~~(RO3, HM4, RO6, WA6, HV6, HM2; all in North Island)~~; while only one ~~(HV5)~~ had a 'meaningful' decrease in *TURB*. Most of these 15 catchments also experienced significant increases in *TN* (9 catchments; 7/9 also 'meaningful') and NO_x (10 catchments; 8/10 also 'meaningful'). Interestingly, *TP* and *DRP* significantly increased in only two of these highly disturbed catchments.

4.6. Multivariate water quality relationships

In order to build on the above correlation analyses, the water quality variables of *CLAR*, *TN*, NO_x, *TP*, and *DRP* were each assessed in a multivariate stepwise regression, using the following ten physiographic and land use independent variables: S_c, *SC%*, P_{ret}, Q_{50}, *NF*, *SG*, *HG*, *PF*, *OW*, and SUD_{cattle} (Table 8). The residual plots for all five water quality variables met the assumptions of normality and linearity, but displayed heteroscedasticity with wide scatter for high values. *CLAR* was correlated to -*HG*, followed by +*OW*, -Q_{50}, and -*PF*, where signs represent whether the relationship is positive (+) or inverse (-). Thus, water clarity was predictably lower for larger rivers that drain larger areas of high-producing grasslands and/or plantation forests, but improved with increased open water coverage (Fig. 5).

The combined stock unit density for beef and dairy cattle (SUD_{cattle}) was the primary predictor for all four nutrient variables, with *TN*, *TP*, and *DRP* also being proportional to plantation forest coverage (*PF*; Table 8). Dissolved oxidized nitrogen (NO_x) was not proportional to *PF*, or any other independent variable in the stepwise regression. Coverage of ~~high-producing grasslands (~~*HG*~~)~~ and silt-clay surface soils (*SC%*) were also proportional factors for TN. Whether intensity or areal coverage, land use was the primary and secondary predictor for all five water quality variables (Fig. 5).

5. Discussion

5.1. River water quality states and trends

We characterized water quality states and trends for 77 river sites across ~~New Zealand~~ ~~(~~NZ~~)~~ using a wide range of flows and water quality conditions for each site, including some small floods. We acknowledge that our analyses did not fully capture large floods due to their short durations, unlikelihood of occurring during the preset monthly sampling, and the fact that we relied on grab samples. These episodic floods are particularly important for ~~the~~ water quality of downstream waters such as lakes and estuaries (Stamm et al., 2014). The uncertainty surrounding our lack of flood samples could have been mitigated by composite samples or supplemental flood samples; however, our 26 years of monthly samples for each site (n = 312) did allow us to confidently report median conditions and temporal trends in water quality (Moosmann et al., 2014).

There was a wide range of water quality across NZ rivers (Table 5), with drastic differences between upland catchments and the more intensively managed lowland catchments~~rivers, distinguished by the 150 m elevation threshold~~. Overall, lowland rivers had considerably lower *CLAR* and higher *TURB*, *TN*, NO_x, *TP*, and *DRP*. ~~For example, visual water clarity (*CLAR*), which is often used as a 'master variable' for overall water quality (Davies-Colley et al., 2003; Julian et al., 2008), was high for upland rivers (mean = 3.2 m), with o~~Only two [alpine glacial flour-affected] upland rivers were below the ANZECC ~~(2000)~~ *CLAR* guideline of 0.6 m~~ (CH3, AX3),~~ ~~. Many of the upland rivers (7/33) had very high water clarity (> 5 m), including one of the clearest non-lake-fed rivers in the world – Motueka River (NN2) with a median *CLAR* of 9.8 m. The lowland rivers, in contrast, had a mean *CLAR* of 1.2 m, with~~ while 17 lowland rivers were~~(39%)~~ below the ANZECC guideline of 0.8 m. ~~Note that these ANZECC (2000) guidelines, which are statistical derivations (i.e. 20th percentile of the first decade of the NRWQN record for 'reference' sites), are merely 'trigger values' that when exceeded trigger a management response to protect ecosystem health (Hart et al., 1999). Although these 'trigger values' are not effects-based standards (which would be difficult to define for the wide variety of NZ ecosystems), they do provide a useful reference for comparing water quality states and trends. Save for a few borderline exceptions, the same sites that were below visual clarity guidelines also exceeded the turbidity trigger values of 4.1 and 5.6 NTU for upland and lowland rivers, respectively.~~

~~Nine of the ten catchments with the highest TN (>740 mg/m^3) were lowland catchments. In all~~Similarly, 13 lowland catchments exceeded the ANZECC *TN* guideline of 614 mg/m^3,~~and~~but only 8 upland catchments exceeded the much lower guideline of 295 mg/m^3. Almost three quarters of these catchments (15/21) also exceeded the NO_x guideline of 444 mg/m^3 (lowland) and 167 mg/m^3 (upland). There were a similar number of sites exceeding ANZECC guidelines for *TP* (33/26 mg/m^3 for lowland/upland) and *DRP* (10/9 mg/m^3 for lowland/upland), each with at least 20 and most of these were corresponding. Our results on the state and trends of the 77 NRWQN catchments generally accord with earlier NRWQN studies (e.g. Ballantine and Davies-Colley, 2014) and a recent publication by Larned et al. (2016), which analyzed water quality states and trends for 461 NZ river sites for the period 2004-2013.

Based on ANZECC (2000) trigger values, we have organized the catchments into four classes (Fig. 6): I. clean river with high visual water clarity (*CLAR*) and low dissolved inorganic nutrients (DIN); II. sediment-impacted river with low *CLAR* and low DIN; III. nutrient-impacted river with high *CLAR* and high DIN; and IV. sediment- and nutrient-impacted river with low *CLAR* and high DIN. Note that the term 'sediment-impacted' is a connotation for total suspended solids (TSS), which includes organic matter as well. In agriculture-dominated catchments, both mineral sediment and particulate organic matter can greatly increase TSS (Julian et al., 2008). We use *CLAR* as a preferred metric for suspended matter because TSS is not routinely measured in the NRWQN (or other monitoring networks) while *CLAR* correlates strongly to TSS (r = -0.92), and better than *TURB* (r = 0.87) (Ballantine et al., 2014). Further, *CDOM* in NZ rivers is low with minimal impact on *CLAR*. We use NO_x as our preferred metric for DIN because it is least affected by suspended sediment and soil properties (compared to *DRP*). However, catchments that exceed ANZECC guidelines for *DRP* are indicated in Fig. 6 by grey-filled markers.

When this classification is combined with the SKSE trend analyses (Table 6), we obtain a clear picture of the current and potential state of NZ rivers (Fig. 6). Before individual rivers are discussed, we first point out key differences between the upland and lowland catchments, which will later be placed within the context of physiography and land use intensity. Most obvious, and consistent with the findings of Larned et al. (2004), was that lowland rivers were much more degraded, particularly by sediment. More than a third of the lowland catchments were either Class II or IV (17/44); whereas, only two upland catchments were Class II. None of the upland catchments were Class IV, and more than two-thirds were clean rivers (Class I). Both types had a similar number of nutrient-impacted rivers (Class III). Particularly concerning is that almost half of the lowland rivers (19/44) are currently experiencing 'meaningful' increases (>1% per year) in *NO_x*, *DRP*, or both. The other striking trend is that many of the lowland rivers are becoming clearer, with 18/44 experiencing 'meaningful' increases ~~(>1% per year)~~ in *CLAR* – which, plausibly, has been attributed to increasing riparian fencing to exclude cattle from channels (Davies-Colley, 2013; Ballantine and Davies-Colley, 2014; Larned et al., 2016).

While clearer rivers are seen as an improvement in water quality; when combined with increasing nutrients, warmer water, and lower flows, the perfect recipe for toxic algae blooms is created (Dodds and Welch, 2000; Hilton et al., 2006). Only recently has the widespread problem of toxic algae blooms in NZ rivers been evidenced (Wood et al., 2015; McAllister et al., 2016), and our results indicate that this problem could worsen given the increasing trends we found in water temperatures, inorganic nutrients, and most influential in our opinion, water clarity. Nutrient enrichment and global warming receive the most attention when it comes to degraded water quality, but rivers have increasingly become light-limited (Hilton et al., 2006; Julian et al., 2013) such that when clarity improves in warm, nutrient-rich rivers, algae can proliferate.

Particularly problematic for NZ is that its lowland catchments, which are warmer~~ (mean median T_w of 13.6 v 10.8 °C for upland rivers)~~, have much greater *DRP* and NO_x, and have longer water residence times, are the ones becoming appreciably clearer (Fig. 6). If droughts become more frequent and intense in NZ, toxic algae blooms are also likely to become more frequent, more widespread, and more problematic. However, this algae response is complex and depends on a number of interacting factors such that the apparent potential for increasing algal nuisance might not necessarily be realized in some rivers (Dodds and Welch, 2000; Hilton et al., 2006).

5.2. The role of physiography in dictating land use intensity across NZ

While physiography did not emerge as a significant independent variable in the multivariate analyses (except *TN* with *SC%*), physiography is important because it largely controls the location and intensity of agricultural land uses. The greatest coverages of high-producing grasslands (*HG*) and the highest densities of cattle (SUD_{cattle}), the two primary explanatory variables for all five major water quality variables (Table 8), were both found predominantly in flat areas with deep soils located in warm, sunny, and relatively dry climates. Livestock in NZ depend almost exclusively on pasture grasses and thus their productivity is maximized when pasture productivity is maximized. The very large cattle are not well suited for steep slopes, particularly dairy cattle which can weigh more than 500 kg. Deep soils are important because they absorb and hold more water for plant uptake, and are not as susceptible to waterlogging, especially in wetter climates. Year-round and intense grazing is best supported by warm and sunny climates where pasture grasses are highly productive and recover quickly following intense grazing such as strip/rotational grazing which is common in NZ dairy farms.

Another soil property we found to be positively correlated to SUD_{cattle} was phosphate retention (P_{ret}). The highest dairy cow densities were found on Allophanic volcanic soils with high P_{ret}, likely because these soils respond favorably to P-fertilizer and thus can be managed more intensively. However, soils with high P_{ret} require more P-fertilizer, and thus generally have higher export of DRP to rivers. Our finding of a significant positive correlation between these two variables is consistent with this interpretation. Further, we found that high-producing pastures with high P_{ret} had the lowest disturbance (D_{HG}), indicating that these intensively managed pastures recover quickly following grazing. In a more comprehensive study of land disturbance across the North Island of NZ, de Beurs et al. (2016) also found that Allophanic soils had the least disturbance among all soil orders. Where high livestock densities occur in less than ideal conditions, land disturbance is likely. Our catchment-scale analyses limit our interpretation of specific situations, but based on our results, field observations and previous remote sensing analyses, pasture disturbance in NZ will likely be highest during droughts on steep, south-facing slopes with thin soils being heavily grazed by sheep. Under these conditions, grasses will be grazed down to bare soil and recover very slowly.

Plantation forests (PF) in NZ also correlated with thick soils with relatively high P_{ret} on flat areas, particularly the pumice soils of the central North Island. The porous nature of the pumice soils allows them to efficiently hold and regulate nutrients, water, and air; while being well-draining and resistant to compaction and flooding. Under these conditions, radiata pine (the dominant PF species in NZ) grows rapidly (mean harvest cycle of 28 y) and can be harvested year-round. Since 1990 however, many of the PF additions have occurred on steeper slopes in response to carbon credit incentives, greater economic demand for wood products (PCE, 2013), and the need for soil erosion control on steep pasture susceptible to land-sliding (Parkyn et al., 2006).

5.3 Land use intensity and water quality in New Zealand rivers

5.3.1 High-producing pastures and livestock densities

High-producing grassland coverage (*HG*) was the primary explanatory variable for visual clarity (*CLAR*; Table 8, Fig. 5). *CLAR* in NZ rivers is mostly influenced by mineral and organic particulates (Davies-Colley et al., 2014). Livestock reduce visual clarity in multiple ways, especially in NZ where high densities of multiple types of livestock tread year-round on relatively steep slopes with highly erodible soils vegetated by shallow-root introduced grasses which are susceptible to destabilization (McDowell et al., 2008). The year-round treading is particularly important because most NZ regions during winter are very wet with short days, which increases soil disturbance (pugging and compaction) and slows recovery times. Where livestock have direct access to rivers, their trampling of riverbanks and instream disturbance is often the main contributor to reduced *CLAR* (Trimble and Mendel, 1995; McDowell et al., 2008).

The lowland flatter areas in NZ have high *HG* coverage and high cattle stock densities (SUD_{cattle}). These lowlands also have high drainage densities – often increased by artificial drainage. The influence of *HG* on *CLAR* is thus exacerbated by this interaction of high SUD_{cattle} and artificial drainage. Interestingly, SUD_{cattle} was not an explanatory variable for *CLAR* in the stepwise regression, which is likely a result of two factors. First, *HG* and SUD_{cattle} are highly correlated, and stepwise regression does not include secondary variables that are explaining the same proportion of variance as the primary independent variable. Second, we found that *CLAR* has actually *improved* in catchments where SUD_{cattle} is high and/or has increased (Fig. 6), which we noted earlier could be a result of increased riparian fencing. In 2003, NZ implemented the *Dairying and Clean Streams Accord*, which has led to the exclusion of dairy cattle from 87% (as of 2012) of perennial rivers greater than 1 m in width (Bewsell et al., 2007; Howard-Williams et al., 2010; Gunn and Rutherford, 2013). By excluding (dairy) cattle from channels and riparian zones, the contribution of riverbank and bed erosion to degraded *CLAR* has likely been mitigated and reduced over time (Trimble and Mendel, 1995; Hughes and Quinn, 2014). Indeed, *CLAR* has been significantly and meaningfully improving in many of NZ's rivers (Table 6), even those with increasing SUD_{cattle}, albeit from a fairly degraded condition. ~~Of the 34 catchments with significant increases in *CLAR*, all but 5 had increases in SUD_{cattle} from 1990 to 2012.~~

Another potential explanation for improved water clarity at numerous sites is the considerable decrease in sheep density across the NZ landscape. NZ had 57.65 million sheep in 1990. By 2012, that number had been reduced by almost half, to 31.19 million (StatsNZ, 2015). Although cattle are larger and have a greater treading impact per animal, the much greater number of sheep means that stock unit density (SUD) may be broadly comparable as regards environmental impact. Another difference is that sheep are generally placed on steeper, less stable slopes in NZ, where headwater stream channels are located. Where there are breaks in slope (even small ones), sheep create tracks of bare soil with their hooves and hillside scars with their bodies (for scratching and shelter), both of which can enhance soil erosion (Evans, 1997). Further, cattle (using their tongues) leave approximately half the grass height on the pasture after grazing; whereas sheep (using their teeth) graze approximately 80% of grass height (down to bare soil in dire conditions), leaving it exposed to erosion (Woodward, 1998). Considering all these factors, sheep can have a greater impact on sediment runoff into rivers, and consequently visual clarity, than suggested by their aversion to water *versus* cattle's attraction to water.

Although not isolated in our analyses, the particulate fractions of *TN* and *TP* have likely been affected by similar processes as *CLAR* and may follow the same temporal trends (Ballantine and Davies-Colley, 2014).

While *HG* was also strongly correlated to river nutrient concentrations (Table 7), the primary explanatory variable for all four major nutrient metrics (Table 8, Fig. 5) was land use intensity as measured by livestock density of beef and dairy cattle (SUD_{cattle}). The difference between these two explanatory variables may seem trivial, however the distinction is important if we want to understand future trends and effectiveness of water quality management strategies. As we demonstrated, the area of land used for high-producing grasslands (*HG*) has not changed much since 1990 (Fig. 2). In fact, it has decreased or stayed virtually the same in all but two of the 77 catchments. Yet, nutrient concentrations have been increasing in many of the rivers (Table 6), which we attribute to (1) increasing numbers of cattle (mostly dairy) on both *HG* and *SG*, and (2) legacy nutrients being slowly delivered to the rivers in groundwater. From 1990 to 2012, NZ approximately doubled its number of dairy cattle, exceeding 6.4 million. (StatsNZ, 2015). This enormous addition to a country that is only 268,000 km^2 in area, has been accompanied by more than 1.426 million tonnes of P-based fertilizers and 335,000 tonnes of N-based fertilizers annually (1990-2012 mean; StatsNZ, 2015). Of the nutrients consumed by lactating dairy cows, approximately 66% of P and 79% of N are returned to the landscape in the form of urine and feces (Monaghan et al., 2007). This results~~, potentially,~~ in about 940,000 tonnes of P-based and 260,000 tonnes of N-based diffuse pollution~~.~~, which is an underestimate because clover-rye grass dairy pastures also receive large inputs from fixed atmospheric N (Ledgard, 2001). Some of these nutrients will be transported to rivers during subsequent storms, but a majority will remain (building up) in the landscape to be slowly added to rivers over decadal time-scales (Howard-Williams et al., 2010).

5.3.2. Plantation forests

All water quality variables were significantly correlated to plantation forest coverage (*PF*; Table 7), with a negative relationship with *CLAR* but positive for all other variables. From the stepwise regression, *PF* emerged as an explanatory variable for all major water quality variables except NO_x (Table 8), suggesting that its dominant impact on river water quality was from surface runoff. Plantation forestry activities can add a considerable amount of sediment and nutrient pollution to rivers, especially during and immediately following harvesting (Fahey et al., 2003; Croke and Hairsine, 2006; Davis, 2005). This harvesting period of maximum soil disturbance usually lasts about two years (Fahey et al., 2003), but the land cover may remain sparsely vegetated and susceptible to erosion for several years (but usually not more than 5 y; de Beurs et al., 2016). The greatest *PF* impact on sediment runoff, and thus potentially *CLAR*, is usually from road sidecast/runoff, shallow landslides, and channel scouring/gullying (Fahey et al., 2003; Motha et al., 2003; Fransen et al., 2001).

Rivers receive a pulse of nutrients during the forest harvest, but fertilizers are also applied at time of re-planting and sometimes routinely to enhance growth (Davis, 2005). Radiata pine in the pumice soils of the central North Island, the dominant area of *PF* in NZ, are particularly responsive to both N- and P-fertilizers and thus likely receive ample supplements. Like pasture fertilizers, some of these nutrients may be delivered to rivers during intense precipitation, but there is also a legacy of nutrients left behind. Fertilizers have been applied to plantation forests in NZ since the 1950s, with an intense period of application in the 1970s

(Davis, 2005). While fertilization rates (tonnes/ha/y) have decreased since 1980, the amount of NO_x leaving catchments mostly covered in *PF* has significantly and 'meaningfully' increased since 1989. None of these catchments had more than 17.7% *HG*, none had major increases in *HG* (< 0.3%), none had major increases in SUD_{cattle} (< 0.7 SU/ha), and none had a significant increase in D_{PF}. What the catchments did have in common were all had gravelly/sandy pumice soils (< 4.5 *SC%*) and all were intensively managed as reported by Davis (2005) and as indicated by high D_C (> 6.8%). The extended periods of nonvegetated land due to weed control also increases the amount of nutrients delivered to rivers over the long term (Davis, 2005).

5.3.3. Land disturbance and water quality

So far, we have discussed how land use, livestock densities, and fertilizer inputs affect~~s~~ water quality, with a focus on sediment and nutrient runoff ~~from high-producing grasslands (*HG*) and plantation forests (*PF*)~~. When land is disturbed (i.e. bare soil), sediment/nutrient mobilization can be enhanced. The most intense and longest lasting disturbances occurred during plantation forest harvests. Following harvest, we found that the land remained disturbed for 1-6 years, with a mean of 1.5 years. The overall mean and median D_{PF} among all catchments was 10%, which means that plantation forestry leaves large areas of disturbed land at any one time. When this bare land is exposed to intense precipitation, large quantities of sediment and nutrients can be mobilized into the rivers. This process has been documented for numerous catchments across NZ ~~happened in the Motueka Catchment (NN1) in 2005 when a 50-y storm fell on some recently-harvested plantation forests. For one of NN1's sub-catchments, the post-harvest disturbed land caused a five-fold increase in sediment yield compared to pre-harvest events. Following this event, sediment yields at NN1 were elevated by a factor of 2-3 over the next 3~~

~~years~~ (Basher et al., 2011; ~~). Similar sediment erosion events for plantation forests during the post-harvest disturbance have been documented for other catchments across NZ (~~Hicks et al., 2000; Phillips et al., 2005). Because these disturbances only last a few years, they typically do not show up as temporal trends (via SKSE); however it is possible that they produce enough readily available sediment to impact water quality for longer periods (Kamarinas et al., 2016).

The coincidence of rainstorms on disturbed pasture could have the same effect on sediment/nutrient runoff if the pasture is connected to the stream network via steep slopes or adjacent channels/canals (Dymond et al., 2010; Kamarinas et al., 2016). Pastures become disturbed from overgrazing, strip grazing, pugging/soil compaction, tilling/reseeding, cropping/harvesting, or landsliding on steep slopes. Given the high intensity of grazing management in NZ, all of these are common. While D_{HG} was lower than D_{PF} on average, D_{HG} had a higher maximum (Table 4). Spatiotemporal patterns in disturbance between these two land uses were also different (de Beurs et al., 2016). D_{PF} covered large areas and lasted years at a time; whereas D_{HG} had two patterns: (1) one related to dairy cattle strip grazing, which were short-lived due to quick recovery times of grasses in fertilized soils; and (2) more widespread and longer continuous disturbances occurring on steeper slopes grazed by sheep and beef cattle, particularly following drought periods. Because our disturbance analyses had a spatial resolution of 463 m, we likely missed some paddock-scale disturbances. Future work could use Landsat imagery (30-m resolution) to assess disturbance (*sensu* de Beurs et al., 2016).

All six catchments with ‘meaningful’ increases in D_{HG} had large increases in dairy cattle density 1990-2012 (~~mean of +1.0 SU/ha across the catchment~~Supplement Tables 3 & 4). Not surprisingly, all six catchments suffered impacts to water quality. Five of the six had ‘meaningful’ increases in *DRP* and three had meaningful increases in NO_x and *TN*. One had a ‘meaningful’ increase in *TURB* and three had significant reductions in *DO*. One of these catchments, in particular, may provide a glimpse into NZ’s future if agricultural intensification continues. The Waingongoro River catchment (WA3) is covered almost entirely by *HG* (91.2%), with practically all of this land being used for intensive strip grazing. The SUD_{da} was 15.0 SU/ha in 1990 and increased to 15.4 SU/ha by 2012. The D_{HG} from 2000-2013 had a strong increasing trend of 9.8%/y RSKSE, associated with the intensification of dairy operations (Wilcock et al., 2009). The result of all this intensification was that WA3 had ‘meaningful’ increases in *TP*~~,~~ and *DRP*~~, and *TN*~~. The ~~only~~ reason *TN* and NO_x did not display ~~a~~ significant trends here is because of the extreme monthly variability in river nitrogen concentrations, possibly due to livestock rotations, fertilizer applications, and precipitation events ~~the catchment was already overloaded with a median river concentration of 1,852 mg/m^3~~. Noteworthy is that these significant trends of increasing SUD_{da}, D_{HG}, and nutrients are occurring not only in lowland catchments on the North Island (WA3, HV2), but also in upland catchments of the North Island (RO6), as well as both lowland (TK1) and upland (CH3, TK2) catchments on the South Island.

While disturbance was not itself a strong predictor of water quality, it did help explain outliers of land use-water quality relationships. For example, streams with high DRP (> 20 mg/m^3; 10th percentile) had one of two dominant land uses, either ~~plantation forest,~~ *PF* (RO2, RO3) or ~~high-producing grassland,~~ *HG* (HM5, WA3, WA9, HM4, HM2). The one exception was RO4, which had relatively low coverage of *PF* (11.2%) and *HG* (2.9%). In fact, RO4 is dominated by NF (79.1%). Upon closer examination, we found that the small areas of *PF* and *HG* in RO4 were disturbed frequently. Further, most of the disturbed forestry occurred on steep slopes and most of the disturbed pastures (practically all sheep and beef) occurred on hilly terrain adjacent to stream channels. Our high temporal-resolution analyses of disturbance showed that even though this catchment is mostly indigenous forest, intense disturbances on small proportions of developed land can have a considerable impact on water quality. RO4 is also experiencing significant increases in *TURB* and *TP*, as well as a significant decrease in *Q*. Another outlier example was RO3, which was the only non-*HG*-dominated catchment with high NO_x (634 mg/m^3). RO3 was dominated by *PF* (69.8%), but it had the highest median disturbance (10.5%) of all catchments. This catchment also exceeds ANZECC guidelines for *DRP* and has experienced meaningful increases in *TURB*, *TN*, and NO_x.

We believe that land disturbance and consequently river water quality~~eutrophication and reduced visual clarity~~ will continue to worsen in some NZ catchments based on the following. More plantation forests were planted 1993-1997 (3,810 km^2) than any other 5-y period in NZ history (NZFFA, 2014). With a 28-y mean age of harvest, NZ will experience its greatest coverage and intensity of forest disturbance around 2025~~, less than 10 years from now~~. When combined with drought and intense storms, the potential for nutrient and sediment mobilization ~~from these lands into NZ's rivers~~ is high, especially given that approximately 45% of these plantings occurred on high-producing grasslands (NZFFA, 2014) where many of the legacy nutrients will be exported to rivers during forest harvest (Davis, 2014). ~~Many of these plantings also occurred on steep slopes, which exacerbates sediment runoff.~~ If carbon prices continue to stay low, there will be a high likelihood that many of the harvested forests will be converted to pasture, adding even more nutrients to NZ rivers (PCE, 2013). Given that the Central Government created a national policy goal of nearly doubling the export to GDP ratio by the year 2025 (MBIE, 2015), NZ is likely to see continued increases in livestock density, fertilizer inputs~~usage~~, and supplemental feed to support these extra livestock, all of which will add even more pressure and risks of eutrophication on NZ's rivers.

Conclusions

This study had the overall goal of describing how changes in land use intensity impact river water quality across broad scales and over long periods. To address this goal we used a combination of 'brute force' statistical analyses (in terms of hundreds of analyses using a suite of physiographic, land use, and water quality data for 77 catchments over 26 years) and careful examination (using multi-resolution data to find patterns and relationships among these variables). This goal was ambitious and we likely missed some relationships and details of water quality changes. However, we found empirical evidence for several key relationships among land use intensity, geomorphic processes, and water quality, which we now place into a broader perspective.

The greatest negative impact on river water quality in ~~New Zealand (~~NZ~~)~~ in recent decades has been high-producing pastures that require large amounts of fertilizer to support high densities of livestock. While this ~~claim~~ finding has been previously published (Davies-Colley, 2013; Howard-Williams et al., 2010; and references within), our results and supporting information show that the relationship between high-producing pastures and water quality is complicated, being dependent on livestock type/density, disturbance regime, and physiography, particularly soil type. Dairy cattle receive much of the blame for degraded water quality because of their high nutrient requirements (Howard-Williams et al., 2010), but beef cattle can also strongly degrade water quality due to comparable required inputs and grazing on steeper land with a higher potential for runoff (McDowell et al., 2008). Further, pasture designations/boundaries are becoming increasingly blurred by modern cattle management, with greater movements of dairy and beef cattle among pastures, greater use of high-producing pastures for beef, over-wintering of dairy cattle on beef pastures, and cross-breeding (Morris, 2013). While riparian fencing has plausibly improved the clarity of NZ rivers, the removal of millions of sheep from steep slopes has also likely played a role that should be investigated further.

New Zealand is the global leading exporter of whole milk powder, butter, and sheep products; and NZ's prominence in these industries is likely to continue over the next decade (OECD/FAO, 2015). In this most recent environmental review by the Organisation for Economic Co-operation and Development, NZ had the highest percent increase (1990-2005) in agricultural production out of 29 OECD countries, the highest percent increase in N-fertilizer use, and the 2nd highest increase in P-fertilizer use. This agricultural intensification over our study period is reflected in overall nutrient enrichment of NZ rivers. If cattle continue to be added at the rates we documented, additional fertilizers and supplemental feed will be needed. Even if best management practices are adopted to reduce nutrient export to rivers, there is already a half-century legacy of nutrients distributed across the NZ landscape that will continue to leak to the rivers (Larned et al., 2016). Indeed, the full impact of agricultural intensification on river water quality will not be fully appreciated for another several decades (Howard-Williams et al., 2010; Vant and Smith, 2004). Having an extensive national network like the NRWQN to document and study these water quality changes will be important.

Author contribution

J. Julian designed the study and performed most of the analyses. K. de Beurs developed the disturbance dataset and performed all trend analyses, both with assistance from B. Owsley. R. Davies-Colley provided water quality dataset and guidance on its use. A.-G. Ausseil developed the stock unit density dataset and provided guidance on land use analyses. J. Julian prepared the manuscript with contributions from all co-authors.

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References

Ausseil, A. G. E., Dymond, J. R., Kirschbaum, M. U. F., Andrew, R. M., and Parfitt, R. L.: Assessment of multiple ecosystem services in New Zealand at the catchment scale, Environmental Modelling & Software, 43, 37-48, 10.1016/j.envsoft.2013.01.006, 2013.

Australian and New Zealand Environment and Conservation Council (ANZECC): Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Volume 1: The Guidelines, National Water Quality Management Strategy, Paper No. 4, Onehunga, 314 pp., 2000.

Ballantine, D. J., and Davies-Colley, R. J.: Water quality trends in New Zealand rivers: 1989–2009, Environmental Monitoring and Assessment, 186, 1939-1950, 10.1007/s10661-013-3508-5, 2014.

Ballantine, D. J., Hughes, A. O., and Davies-Colley, R. J.: Mutual relationships of suspended sediment, turbidity and visual clarity in New Zealand rivers, in: Proceedings of the International Association of Hydrological Sciences, New Orleans, 265-271, 2014.

Baron, J. S., Poff, N. L., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston, N. G., Jackson, R. B., Johnston, C. A., Richter, B. D., and Steinman, A. D.: Meeting ecological and societal needs for freshwater, Ecological Applications, 12, 1247-1260, 2002.

Basher, L. R., Hicks, D. M., Clapp, B., and Hewitt, T.: Sediment yield response to large storm events and forest harvesting, Motueka River, New Zealand, New Zealand Journal of Marine and Freshwater Research, 45, 333-356, 2011.

Bewsell, D., Monaghan, R. M., and Kaine, G.: Adoption of stream fencing among dairy farmers in four New Zealand catchments, Environmental Management, 40, 201-209, 2007.

Blüthgen, N., Dormann, C. F., Prati, D., Klaus, V. H., Kleinebecker, T., Hölzel, N., Alt, F., Boch, S., Gockel, S., Hemp, A., Müller, J., Nieschulze, J., Renner, S. C., Schöning, I., Schumacher, U., Socher, S. A., Wells, K., Birkhofer, K., Buscot, F., Oelmann, Y., Rothenwöhrer, C., Scherber, C., Tscharntke, T., Weiner, C. N., Fischer, M., Kalko, E. K. V., Linsenmair, K. E., Schulze, E.-D., and Weisser, W. W.: A quantitative index of land-use intensity in grasslands: Integrating mowing, grazing and fertilization, Basic and Applied Ecology, 13, 207-220, http://dx.doi.org/10.1016/j.baae.2012.04.001, 2012.

Boesch, D. F.: Challenges and opportunities for science in reducing nutrient over-enrichment of coastal ecosystems, Estuaries, 25, 886-900, 10.1007/bf02804914, 2002.

Brauman, K. A., Daily, G. C., Duarte, T. K., and Mooney, H. A.: The nature and value of ecosystem services: An overview highlighting hydrologic services, in: Annual Review of Environment and Resources, Annual Review of Environment and Resources, Annual Reviews, Palo Alto, 67-98, 2007.

Brierley, G. P.: Landscape memory: the imprint of the past on contemporary landscape forms and processes, Area, 42, 76-85, 2010.

Campbell, N., D'Arcy, B., Frost, A., Novotny, V., Sansom, A.: Diffuse pollution. An introduction to the problems and solutions, IWA publishing, London, 322 pp., 2004.

Cleveland, W. S., and Devlin, S .J.: Locally weighted regression: An approach to regression analysis by local fitting, Journal of the American Statistical Association, 83, 596-610, 1988.

Close, M. E., and Davies-Colley, R. J.: Baseflow water chemistry in New Zealand rivers 1. Characterisation, New Zealand Journal of Marine and Freshwater Research, 24, 319-341, 10.1080/00288330.1990.9516428, 1990.

Croke, J. C., and Hairsine, P. B.: Sediment delivery in managed forests: a review, Environmental Reviews, 14, 59-87, 10.1139/a05-016, 2006.

Davies-Colley, R. J.: River water quality in New Zealand: An introduction and overview, in: Ecosystem Services in New Zealand - Conditions and Trends, edited by: Dymond, J. R., Manaaki Whenua Press, Lincoln, 432-447, 2013.

Davies-Colley, R. J., Vant, W. N., and Smith, D. G.: Colour and Clarity of Natural Waters: Science and Management of Optical Water Quality, Blackburn Press, Caldwell, 310 pp., 2003.

Davies-Colley, R. J., Smith, D. G., Ward, R. C., Bryers, G. G., McBride, G. B., Quinn, J. M., and Scarsbrook, M. R.: Twenty years of New Zealand's National Rivers Water Quality Network: Benefits of careful design and consistent operation, Journal of the American Water Resources Association, 47, 750-771, 2011.

Davies-Colley, R. J., Ballantine, D. J., Elliott, A. H., Swales, A., Hughes, A. O., and Gall, M. P.: Light attenuation – a more effective basis for the management of fine suspended sediment than mass concentration?, Water Science and Technology, 69, 1867-1874. doi: 10.2166/wst.2014.096, 2014.

Davis, M.: Nutrient losses from forestry in the Lake Taupo catchment, Environment Waikato Technical Report 2005/37, Hamilton, 22, 2005.

Davis, M.: Nitrogen leaching losses from forests in New Zealand, New Zealand Journal of Forestry Science, 44, 1-14, 10.1186/1179-5395-44-2, 2014.

de Beurs, K. M., Owsley, B. C., and Julian, J. P.: Disturbance analyses of forests and grasslands with MODIS and Landsat in New Zealand, International Journal of Applied Earth Observation and Geoinformation, 45, Part A, 42-54, http://dx.doi.org/10.1016/j.jag.2015.10.009, 2016.

Dodds, W. K., and Welch, E. B.: Establishing nutrient criteria in streams, Journal of the North American Benthological Society, 19, 186-196, 2000.

Dymond, J. R., Betts, H. D., and Schierlitz, C. S.: An erosion model for evaluating regional land-use scenarios, Environmental Modelling & Software, 25, 289-298, 10.1016/j.envsoft.2009.09.011, 2010.

Ekholm, P., Rankinen, K., Rita, H., Räike, A., Sjöblom, H., Raateland, A., Vesikko, L., Cano Bernal, J. E., and Taskinen, A.: Phosphorus and nitrogen fluxes carried by 21 Finnish agricultural rivers in 1985–2006, Environmental Monitoring and Assessment, 187, 1-17, 10.1007/s10661-015-4417-6, 2015.

Erb, K.-H., Haberl, H., Jepsen, M. R., Kuemmerle, T., Lindner, M., Müller, D., Verburg, P. H., and Reenberg, A.: A conceptual framework for analysing and measuring land-use intensity, Current Opinion in Environmental Sustainability, 5, 464-470, http://dx.doi.org/10.1016/j.cosust.2013.07.010, 2013.

Erb, K.-H., Fetzel, T., Haberl, H., Kastner, T., Kroisleitner, C., Lauk, C., Niedertscheider, M., and Plutzar, C.: Beyond Inputs and Outputs: Opening the Black-Box of Land-Use Intensity, in: Social Ecology: Society-Nature Relations across Time and Space, edited by: Haberl, H., Fischer-Kowalski, M., Krausmann, F., and Winiwarter, V., Springer International Publishing, Cham, 93-124, 2016.

Evans, R.: Soil erosion in the UK initiated by grazing animals, Applied Geography, 17, 127-141, http://dx.doi.org/10.1016/S0143-6228(97)00002-7, 1997.

Fahey, B. D., Marden, M., and Phillips, C. J.: Sediment yields from plantation forestry and pastoral farming, coastal Hawke's Bay, North Island, New Zealand, Journal of Hydrology (New Zealand), 42, 27-38, 2003.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., and Snyder, P. K.: Global consequences of land use, Science, 309, 570-574, 2005.

Forest Owners Association (FOA): New Zealand plantation forest industry: Facts and figures 2011/2012, Ministry for Primary Industries, Wellington, 46 pp., 2012.

Fransen, P. J. B., Phillips, C. J., and Fahey, B. D.: Forest road erosion in New Zealand: overview, Earth Surface Processes and Landforms, 26, 165-174, 10.1002/1096-9837(200102)26:2<165::AID-ESP170>3.0.CO;2-#, 2001.

Grohmann, C. H., Smith, M. J., and Riccomini, C.: Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland, IEEE Transactions on Geoscience and Remote Sensing, 49, 1200-1213, 2011.

Gunn, A., and Rutherford, C.: The Dairying and Clean Streams Accord: Snaphot of Progress 2011/2012, Ministry for Primary Industries, Wellington, 12, 2013.

Hart, B. T., Maher, B., and Lawrence, I.: New generation water quality guidelines for ecosystem protection, Freshwater Biology, 41, 347-359, 10.1046/j.1365-2427.1999.00435.x, 1999.

Hicks, D. M., Gomez, B., and Trustrum, N. A.: Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand, Water Resources Research, 36, 1129-1142, 10.1029/1999WR900340, 2000.

Hilton, J., O'Hare, M., Bowes, M. J., and Jones, J. I.: How green is my river? A new paradigm of eutrophication in rivers, Science of the Total Environment, 365, 66-83, 2006.

Howard-Williams, C., Davies-Colley, R., Rutherford, K., and Wilcock, R.: Diffuse pollution and freshwater degradation: New Zealand Perspectives, International Conference of the IWA Diffuse Pollution Specialist Group, Beaupre, Quebec, 2010.

Hughes, A. O., and Quinn, J. M.: Before and After Integrated Catchment Management in a Headwater Catchment: Changes in Water Quality, Environmental Management, 54, 1288-1305, 10.1007/s00267-014-0369-9, 2014.

Julian, J. P., Doyle, M. W., Powers, S. M., Stanley, E. H., and Riggsbee, J. A.: Optical water quality in rivers, Water Resources Research, 44, W10411, doi:10410.11029/12007WR006457, 2008.

Julian, J. P., Davies-Colley, R. J., Gallegos, C. L., and Tran, T. V.: Optical Water Quality of Inland Waters: A Landscape Perspective, Annals of the Association of American Geographers, 103, 309-318, 2013.

Kamarinas, I., Julian, J. P., Hughes, A. O., Owsley, B. C., and de Beurs, K. M.: Nonlinear changes in land cover and sediment runoff in a New Zealand catchment dominated by plantation forestry and livestock grazing, Water, 8, 436, doi:10.3390/w8100436, 2016.

Kronvang, B., Andersen, H. E., Børgesen, C., Dalgaard, T., Larsen, S. E., Bøgestrand, J., and Blicher-Mathiasen, G.: Effects of policy measures implemented in Denmark on nitrogen pollution of the aquatic environment, Environmental Science & Policy, 11, 144-152, http://dx.doi.org/10.1016/j.envsci.2007.10.007, 2008.

Kuemmerle, T., Erb, K., Meyfroidt, P., Müller, D., Verburg, P. H., Estel, S., Haberl, H., Hostert, P., Jepsen, M. R., Kastner, T., Levers, C., Lindner, M., Plutzar, C., Verkerk, P. J., van der Zanden, E. H., and Reenberg, A.: Challenges and opportunities in mapping land use intensity globally, Current Opinion in Environmental Sustainability, 5, 484-493, http://dx.doi.org/10.1016/j.cosust.2013.06.002, 2013.

Landcare Research (LCR): New Zealand Land Cover Database, available at: http://www.lcdb.scinfo.org.nz/, 2015.

Larned, S. T., Scarsbrook, M. R., Snelder, T. H., Norton, N. J., and Biggs, B. J. F.: Water quality in low-elevation streams and rivers of New Zealand: recent state and trends in contrasting land-cover classes, New Zealand Journal of Marine and Freshwater Research, 38, 347-366, 2004.

Larned, S., Snelder, T., Unwin, M., and McBride, G.: Water quality in New Zealand rivers: current state and trends, New Zealand Journal of Marine and Freshwater Research, DOI: 10.1080/00288330.2016.1150309, 2016.

Ledgard, S. F.: Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures, Plant and Soil, 228, 43-59, 10.1023/a:1004810620983, 2001.

Lobser, S. E., and Cohen, W.B.: MODIS tasselled cap: land cover characteristicsexpressed through transformed MODIS data, Int. J. Remote Sens., 28,5079–5101, 2007.

McAllister, T. G., Wood, S. A., and Hawes, I.: The rise of toxic benthic Phormidium proliferations: a review of their taxonomy, distribution, toxin content and factors regulating prevalence and increased severity, Harmful Algae, 55, 282-294, 2016.

McDowell, R. W., Houlbrooke, D. J., Muirhead, R. W., Muller, K., Shepherd, M., and Cuttle, S. P.: Grazed Pastures and Surface Water Quality, Nova Science Publishers, New York, 238 pp., 2008.

Ministry of Business, Innovation & Employment (MBIE): Business Growth Agenda: 2015, available at: http://www.mbie.govt.nz/info-services/business/business-growth-agenda/pdf-and-image-library/towards-2025/mb13078-1139-bga-report-01-export-markets-09sept-v17-fa-web.PDF, 2015.

Ministry for the Environment (MfE): Land-use and carbon analysis system (LUCAS): Satellite imagery interpretation guide for land-use classes (2nd edition), Ministry for the Environment, Wellington, 73 pp., 2012.

Monaghan, R. M., Hedley, M. J., Di, H. J., McDowell, R. W., Cameron, K. C., and Ledgard, S. F.: Nutrient management in New Zealand pastures— recent developments and future issues, N. Z. J. Agric. Res., 50, 181-201, 10.1080/00288230709510290, 2007.

Moosmann, L., Müller, B., Gächter, R., Wüest, A., Butscher, E., and Herzog, P.: Trend-oriented sampling strategy and estimation of soluble reactive phosphorus loads in streams, Water Resources Research, 41, W01020, 10.1029/2004WR003539, 2005.

Morris, S. T.: Sheep and beef cattle production systems, in: Ecosystem Services in New Zealand - Conditions and Trends, edited by: Dymond, J. R., Manaaki Whenua Press, Lincoln, 79-84, 2013.

Motha, J. A., Wallbrink, P. J., Hairsine, P. B., and Grayson, R. B.: Determining the sources of suspended sediment in a forested catchment in southeastern Australia, Water Resources Research, 39, 1056, doi:1010.1029/2001WR000794, 2003.

Newsome, P. F. J., R.H., W., and Willoughby, E. J.: Land Resource Information System Spatial Data Layers: Data Dictionary, Palmerston North, 75, 2008.

New Zealand Farm Forestry Association (NZFFA): National Exotic Forest Description: as at 1 April 2014, Ministry for Primary Industries, Wellington, 77 pp., 2014.

OECD/FAO: OECD-FAO Agricultural Outlook 2015-2024, OECD/Food and Agriculture Organization of the United Nations Paris, 148, 2015.

Parkyn, S. M., Davies-Colley, R. J., Scarsbrook, M. R., Halliday, N. J., Nagels, J. W., Marden, M., and Rowan, D.: Pine afforestation and stream health: a comparison of land-use in two soft rock catchments, East Cape, New Zealand, New Zealand Natural Sciences, 31, 113-135, 2006.

Parliamentary Commissioner for the Environment (PCE): Water quality in New Zealand: land use and nutrient pollution, Parliamentary Commissioner for the Environment, Wellington, 82 pp., available at: http://www.pce.parliament.nz/media/1275/pce-water-quality-land-use-web-amended.pdf, 2013.

Phillips C. J., Marden M., and Rowan D.: Sediment yield following plantation harvesting, Coromandel Peninsula, North Island, New Zealand, Journal of Hydrology (NZ), 44, 29-44, 2005.

Ramankutty, N., Graumlich, L., Achard, F., Alves, D., Chhabra, A., DeFries, R. S., Foley, J. A., Geist, H., Houghton, R. A., Goldewijk, K. K., Lambin, E. F., Millington, A., Rasmussen, K., Reid, R. S., and Turner, B. L.: Global Land-Cover Change: Recent Progress, Remaining Challenges, in: Land-Use and Land-Cover Change: Local Processes and Global Impacts, edited by: Lambin, E. F., and Geist, H., Springer Berlin Heidelberg, Berlin, Heidelberg, 9-39, 2006.

Saunders, W. M. H.: Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter, and other soil properties, N. Z. J. Agric. Res., 8, 30-57, DOI: 10.1080/00288233.1965.10420021, 1965.

Scarsbrook, M. R.: State and trends in the National River Water Quality Network (1989-2005), Ministry for the Environment, ME number 778, 48 pp., available at: http://www.mfe.govt.nz/publications/ser/water-quality-network-nov06/index.html, 2006.

Scarsbrook, M. R., McBride, C. G., McBride, G. B., and Bryers, G. G.: Effects of climate variability on rivers: Consequences for long term water quality analysis, Journal of the American Water Resources Association, 39, 1435-1447, 2003.

Smith, D. G., McBride, G. B., Bryers, G. G., Wisse, J., and Mink, D. F. J.: Trends in New Zealand's National River Water Quality Network, New Zealand Journal of Marine and Freshwater Research, 30, 485-500, 10.1080/00288330.1996.9516737, 1996.

Smith, D. G., Davies-Colley, R. J., Knoeff, J., and Slot, G. W. J.: Optical characteristics of New Zealand rivers in relation to flow, Journal of the American Water Resources Association, 33, 301–312, 1997.

Snelder, T. H.: Definition of a multivariate classification of New Zealand Lakes, National Institute of Water & Atmospheric Research Ltd, Christchurch, 32, 2006.

Snelder, T., Biggs, B., and Weatherhead, M.: New Zealand River Environment Classification User Guide (REC, v2), Produced for the Ministry for the Environment by the National Institute of Water and Atmospheric Research (NIWA), Publication number ME 1026, 2010.

Stamm, C., Jarvie, H. P., and Scott, T.: What's More Important for Managing Phosphorus: Loads, Concentrations or Both?, Environmental science & technology, 48, 23-24, 10.1021/es405148c, 2014.

Statistics New Zealand (StatsNZ): 2012 Agricultural Census tables, available at: http://www.stats.govt.nz/browse_for_stats/industry_sectors/agriculture-horticulture-forestry/2012-agricultural-census-tables/livestock.aspx, 2015.

Tait, A., and Turner, R.: Generating Multiyear Gridded Daily Rainfall over New Zealand, Journal of Applied Meteorology, 44, 1315-1323, 10.1175/JAM2279.1, 2005.

Trimble, S. W., and Mendel, A. C.: The cow as a geomorphic agent—A critical review, Geomorphology, 13, 233–253, 1995.

Vant, B., and Smith, P.: Nutrient concentrations and water ages in 11 streams flowing into LakeTaupo, Environment Waikato Technical Report 2002/18R, 26, 2004.

Varanka, S., and Luoto, M.: Environmental determinants of water quality in boreal rivers based on partitioning methods, River Research and Applications, 28, 1034-1046, 10.1002/rra.1502, 2012.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M.: Human domination of Earth's ecosystems, Science, 277, 494, 1997.

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M.: Global threats to human water security and river biodiversity, Nature, 467, 555-561, 2010.

Webb, T. W., and Wilson, A. D.: A Manual of Land Characteristics for Evaluation of Rural land, Landcare Research New Zealand Ltd, Lincoln, 1995.

Wilcock, R. J., Betteridge, K., Shearman, D., Fowles, C. R., Scarsbrook, M. R., Thorrold, B. S., and Costall, D.: Riparian protection and on-farm best management practices for restoration of a lowland stream in an intensive dairy farming catchment: A case study, New Zealand Journal of Marine and Freshwater Research, 43, 803-818, doi:10.1080/00288330909510042, 2009.

Wilmshurst, J. M., Anderson, A. J., Higham, T. F. G., Worthy, T. H.: Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat, Proceedings of the National Academy of Sciences, 105, 7676-7680, 2008.

Wood, S., Hawes, I., McBride, G., Truman, P., and Dietrich, D.: Advice to inform the development of a benthic cyanobacteria attribute, Cawthron Institute, Report No. 2752, Nelson, 91, 2015.

Woods, R., Bidwell, V., Clothier, B., Green, S., Elliott, S., Shankar, U., Harris, S., Hewitt, A., Gibb, R., Parfitt, R., and Wheeler, D.: The CLUES Project: Predicting the effects of land-use on water quality - Stage II, National Institute of Water & Atmospheric Research, Christchurch, 2006.

Woodward, S. J. R.: Bite mechanics of cattle and sheep grazing grass-dominant swards, Applied Animal Behaviour Science, 56, 203-222, 1998.

Zobrist, J., and Reichert, P.: Bayesian estimation of export coefficients from diffuse and point sources in Swiss watersheds, Journal of Hydrology, 329, 207-223, http://dx.doi.org/10.1016/j.jhydrol.2006.02.014, 2006.

Tables

Table 1. Water quality variables measured by the National River Water Quality Network (NRWQN) obtained from monthly grab samples from 1989 to 2014 for 77 catchments. Details on analytical methods can be found in Davies-Colley et al. (2011).

Variable	**Definition (units)**
Q	Water discharge (m^3/s)
T_w	Water temperature (°C)
DO	Dissolved oxygen (%)
$COND$	Water conductivity (µS/cm)
pH_W	Water pH ($-\log_{10}[H^+]$)
$CLAR$	Horizontal visual water clarity from black disc sighting range (m)
$TURB$	Water turbidity (NTU)
$CDOM$	Colored dissolved organic matter, measured as spectrophotometric absorbance of a membrane filtrate at 440 nm (m^{-1})
TN	Total nitrogen (mg/m^3)
NO_x	Oxidized nitrogen in nitrate and nitrite forms (mg/m^3)
TP	Total phosphorus (mg/m^3)
DRP	Dissolved reactive phosphorus (mg/m^3)

Table 2. Landscape variables characterizing the 77 catchments of the National River Water Quality Network (NRWQN). More details on sources for these data can be found in Methods section.

Variable	Definition (units)	Source (resolution/scale)
Morphometric variables		
Area (A)	Total catchment area above monitoring site (km^2)	National Elevation Dataset (30 m)
Drainage density (D_d)	Total length of streams per catchment area (km/km^2)	River Environment Classification, v2 (1:24,000)
Catchment slope (S_c)	Mean slope across entire catchment (degrees)	National Elevation Dataset (30 m)
Ruggedness (R_r)	Standard deviation of catchment slope (degrees)	National Elevation Dataset (30 m)
Soil variables		
Silt-clay percentage ($SC\%$)	Percentage of catchment surface soils dominated by clayey or silty soils (%)	Fundamental Soil Layers (1:63,360)
Soil depth (Z_s)	Mean maximum potential rooting depth across catchment (m)	Fundamental Soil Layers (1:63,360)
Soil pH (pH_S)	Mean pH at 0.2-0.6 m depth across catchment ($-\log_{10}[H^+]$)	Fundamental Soil Layers (1:63,360)
Cation exchange capacity (CEC)	Weighted mean CEC at 0-0.6 m depth across catchment (cmoles [+]/kg)	Fundamental Soil Layers (1:63,360)
Organic matter percentage ($OM\%$)	Weighted mean of total carbon at 0-0.2 m depth across catchment (%)	Fundamental Soil Layers (1:63,360)
Phosphate retention (P_{ret})	Weighted mean of phosphate retention at 0-0.2 m depth across catchment (%)	Fundamental Soil Layers (1:63,360)
Hydro-climatological variables		
Median annual precipitation (MAP)	Median annual precipitation averaged across catchment (mm/y)	NIWA National Climate Database (5 km)
Median annual temperature (MAT)	Median annual temperature averaged across catchment (°C)	NIWA National Climate Database (5 km)
Median annual sunshine (MAS)	Median annual sunshine hours averaged across catchment (hours/y)	NIWA National Climate Database (5 km)
Median discharge (Q_{50})	Median discharge from NRWQN samples during 1989-2014 (m^3/s)	NRWQN (catchment)

Relative water storage (*RWS*)	Proportion of annual Q_{50} stored in reservoirs/lakes (m^3/m^3)	Freshwater Environments New Zealand (1:50,000)
Land Use and Land Disturbance variables		
Land use	Percent of catchment that is occupied by each land use (%); see Table 3 for land uses	Land Cover Database (LCDB, v 4.1), 2001 (1 ha)
High-producing pasture disturbance (D_{HG})	Percent of high-producing grasslands within catchment that is disturbed (%), based on aggregate of 463-m pixels within catchment	de Beurs et al., 2016 (463 m; 8-day)
Plantation forestry disturbance (D_{PF})	Percent of plantation forestry within catchment that is disturbed (%), based on aggregate of 463-m pixels within catchment	de Beurs et al., 2016 (463 m; 8-day)
Catchment disturbance (D_C)	Percent of catchment that is disturbed (%), based on aggregate of 463-m pixels within catchment	de Beurs et al., 2016 (463 m; 8-day)
Stock unit density (*SUD*)	Catchment-averaged stock unit density for dairy ($_{da}$), beef ($_{be}$), deer ($_{de}$), and sheep ($_{sh}$) in 2011 (SU/ha); subscripts are used to isolate SUD by livestock type	Ausseil et al., 2013 (1 ha)
Change in stock unit density ($SUD_{2012\text{-}1990}$)	Difference between SUD in 2012 and 1990 (SU/ha)	Statistics NZ (territorial authority)

Table 3. Land use classification used in this study, aggregated from the LUCAS (v11) and LCDB (v4.1) land use/cover datasets.

Class (abbreviation)	**Description**	**LUCAS classes**	**LCDB classes**	**2012 national coverage (%) LUCAS / LCDB**
Non-plantation forest (NF)	All non-plantation forests ≥ 5m; does not include Manuka/Kanuka	71	68, 69	29.2 / 23.9
Plantation forest (PF)	All forests that are planted for the purpose of harvesting	72,73	64, 71	7.9 / 7.6
Shrub/Grassland (SG)	All shrubs < 5m and grasses that are not intensively managed	74, 76	41-44, 50-58	33.0 / 25.4
High-producing grassland (HG)	High-quality pasture grasses that are intensively managed	75	40	21.6 / 33.0
Perennial cropland (PC)	Orchards and vineyards	77	33	0.4 / 0.4
Annual cropland (AC)	All annual crops and cultivated bare ground	78	30	1.4 / 1.4
Open water (OW)	Rivers, lakes/reservoirs, ponds, and estuaries	79	20-22	1.9 / 2.0
Vegetated wetland (VW)	Herbaceous or woody vegetation periodically flooded; includes mangroves	80	45-47, 70	0.5 / 0.7
Urban (UR)	Built-up areas, infrastructure, transportation networks, and urban parks/open spaces	81	1-5	0.8 / 0.9
Barren/Other (BO)	Bare rock, sand, gravel and other areas not dominated by vegetation; includes mining and permanent ice/snow	82	6-16	3.3 / 4.8

Table 4. Statistical description of landscape variables for the 77 NRWQN catchments. Refer to Tables 2 and 3 for variable descriptions.

Variable	**Units**	**Minimum**	**Median**	**Maximum**	**Mean ± SD**
Morphometric Variables					
Area (*A*)	km^2	26	1126	20539	2639 ± 3714
Drainage density (D_d)	km/km^2	1.30	1.59	2.61	1.60 ± 0.16
Catchment slope (S_c)	degrees	3.4	15.9	30.3	16.3 ± 6.8
Ruggedness (R_r)	degrees	3.4	10.8	15.8	10.6 ± 2.4
Soil Variables					
Silt-clay percentage (*SC%*)	%	0	47.3	98.7	44.0 ± 31.6
Soil depth (Z_s)	m	0.55	0.96	1.50	1.02 ± 0.22
Soil pH (*pH*)	$-\log_{10}[H^+]$	4.8	5.6	6.5	5.6 ± 0.3
Cation exchange capacity (*CEC*)	cmoles [+]/kg	11.6	18.7	33.5	18.8 ± 4.6
Organic matter percentage (*OM%*)	%	2.8	6.7	23.2	7.2 ± 2.9
Phosphate retention (P_{ret})	%	19.9	39.0	77.8	41.5 ± 12.2
Hydro-climatological Variables					
Median annual precipitation (*MAP*)	mm/y	533	1652	7044	1778 ± 873
Median annual temperature (*MAT*)	°C	5.0	9.9	15.1	9.9 ± 2.4
Median annual sunshine (*MAS*)	hours/y	1325	1856	2116	1841 ± 146
Median discharge (Q_{50})	m^3/s	0.4	26.0	515.0	69.6 ± 112.6
Relative water storage (*RWS*)	m^3/m^3	0	0	29.2	1.1 ± 3.7
Land Use Variables					
Non-plantation forest (*NF*)	%	0.1	20.5	94.1	26.7 ± 23.3
Plantation forest (*PF*)	%	0	3.3	69.8	8.2 ± 12.3
Shrub/Grassland (*SG*)	%	0.4	21.7	82.3	26.6 ± 20.2
High-producing grassland (*HG*)	%	0	21.6	91.2	30.9 ± 26.2
Perennial cropland (*PC*)	%	0	0	1.3	0.1 ± 0.2
Annual cropland (*AC*)	%	0	0.1	7.9	0.6 ± 1.4
Open water (*OW*)	%	0	0.4	25.6	1.9 ± 4.3

Vegetated wetland (*VW*)	%	0	0.1	2.2	0.3 ± 0.4
Urban (*UR*)	%	0	0.1	5.8	0.4 ± 0.7
Barren/Other (*BO*)	%	0	1.3	30.0	4.4 ± 6.5
			Land Disturbance Variables		
Catchment disturbance (D_C)	%	0	3.4	10.5	3.6 ± 2.1
HG disturbance (D_{HG})	%	0	4.4	34.9	6.0 ± 6.4
PF disturbance (D_{PF})	%	0	9.9	27.8	10.4 ± 6.7
Stock unit density (*SUD*)	SU/ha	0	2.2	16.1	3.2 ± 3.1
Dairy SUD (SUD_{da})	SU/ha	0	0.2	15.4	1.2 ± 2.4
Beef SUD (SUD_{be})	SU/ha	0	0.5	3.5	0.7 ± 0.8
Sheep SUD (SUD_{sh})	SU/ha	0	0.6	4.5	1.2 ± 1.3
Deer SUD (SUD_{de})	SU/ha	0	0	0.2	0 ± 0

Table 5. Statistical description of medians of water quality variables for the 77 NRWQN catchments. Note that the ratio of mean/median can be used as an index of data skewness.

Variable	**Units**	**Minimum**	**Median**	**Maximum**	**Mean ± SD**
T_w	°C	7.2	12.2	16.9	12.4 ± 2.4
DO	%	75.5	100.8	113.1	100.0 ± 4.7
COND	µS/cm	39	92	528	113 ± 83
pH_W	$-\log_{10}[H^+]$	6.9	7.7	8.5	7.7 ± 0.3
CLAR	m	0.1	1.5	9.8	2.1 ± 1.8
TURB	NTU	0.3	2.1	82	4.2 ± 9.4
CDOM	m^{-1}	0.1	0.7	4.6	0.9 ± 0.8
TN	mg/m^3	40	259	2162	369 ± 361
NO_x	mg/m^3	1	107	1852	230 ± 302
TP	mg/m^3	3	15	115	24 ± 24
DRP	mg/m^3	0.5	5.0	66.2	8.6 ± 11.2

Table 6. River water quality trends from 1989-2014. The table reports numbers of sites (out of 77) in different categories of water quality time trend. All variables were flow-adjusted except flow and water temperature. Significant trends were taken to be those with a p-value < 0.05 in the Seasonal Kendall test. Meaningful trends were taken to be those which also had a magnitude (RSKSE) greater than 1% per year.

Direction of trend	River Water Quality Variable (1989-2014)											
	Q	***T_w***	***DO***	***COND***	***pH_w***	***CLAR***	***TURB***	***CDOM***	***TP***	***DRP***	***TN***	***NO_x***
Meaningful Increase	1	0	0	4	0	29	17	1	8	17	27	24
Significant Increase	1	21	6	48	12	5	1	1	6	3	6	3
No Significant Trend	67	54	42	19	48	39	50	56	52	49	39	37
Significant Decrease	3	2	29	6	17	2	0	13	4	5	3	1
Meaningful Decrease	5	0	0	0	0	2	9	6	7	3	2	12

Table 7. Correlations of water quality (median values) vs. the major land uses, livestock densities, and median catchment disturbance of the 77 NRWQN catchments. All values represent Spearman correlation coefficients (r_s). Nonsignificant relationships ($p \geq 0.05$) are denoted by *NS*. T_w was not included because of its strong latitudinal trend. *DO* and pH_w were not included because they had no significant relationships with land use. SUD_{cattle} is the combination of dairy and beef cattle.

	HG	***SG***	***NF***	***PF***	***OW***	SUD_{da}	SUD_{be}	SUD_{cattle}	SUD_{sh}	SUD_{de}	D_C	D_{HG}	D_{PF}
COND	0.57	-0.53	*NS*	0.53	*NS*	0.44	0.63	0.60	0.35	*NS*	*NS*	-0.25	*NS*
CLAR	-0.45	*NS*	0.28	-0.31	*NS*	-0.41	-0.49	-0.49	-0.40	*NS*	*NS*	*NS*	-0.27
TURB	0.46	*NS*	-0.27	0.28	*NS*	0.38	0.50	0.48	0.40	*NS*	*NS*	*NS*	*NS*
CDOM	0.56	-0.55	*NS*	0.24	-0.29	0.48	0.53	0.57	0.24	*NS*	*NS*	-0.33	*NS*
TN	0.82	-0.56	-0.37	0.46	-0.25	0.79	0.75	0.85	0.60	0.26	*NS*	-0.40	*NS*
NO_x	0.70	-0.53	-0.25	0.44	-0.25	0.77	0.65	0.79	0.51	0.28	*NS*	-0.39	*NS*
TP	0.66	-0.54	-0.32	0.48	*NS*	0.58	0.66	0.72	0.42	*NS*	*NS*	-0.24	*NS*
DRP	0.59	-0.65	*NS*	0.50	-0.43	0.58	0.58	0.66	0.31	*NS*	*NS*	-0.32	*NS*

Table 8. Stepwise regressions of water quality variables (median values) on landscape descriptors (forward selection, $p < 0.05$). Signs of coefficients indicate whether the relationship is proportional (+) or inverse (-). Int is model intercept. Scatterplots that characterize the primary and secondary explanatory variables are displayed in Figure 5.

Water Quality Variable	**Step**	**Landscape Variable**	**Model Estimate**	**Multivariate sequential r^2**
CLAR	1	*HG*	-0.03	0.17
	2	*OW*	0.18	0.27
	3	Q_{50}	-0.01	0.35
	4	*PF*	-0.03	0.39
	Int		3.16	
TN	1	SUD_{cattle}	77.05	0.62
	2	*HG*	4.26	0.68
	3	*PF*	5.16	0.69
	4	*SC%*	1.80	0.72
	Int		-33.95	
NO_x	1	SUD_{cattle}	86.15	0.58
	Int		62.65	
TP	1	SUD_{cattle}	5.47	0.41
	2	*PF*	0.64	0.52
	Int		7.75	
DRP	1	SUD_{cattle}	2.23	0.31
	2	*PF*	0.38	0.48
	Int		1.14	

Figures

Figure 1. Land use and location of the 77 National River Water Quality Network (NRWQN) catchments. Catchment ID colors refer to dominant land use (>50%). Catchments with no dominant land use are black.

Figure 2. Changes in land use areal coverage, livestock, and fertilizer inputs across New Zealand 1989/1990 vs. 2011/2012. Nitrogen fertilizers include urea and ammonium sulphate. Phosphorus fertilizers include superphosphate and diammonium phosphate.

Figure 3. Disturbance frequency of North Island per 463-m pixel, based on interpretation of MODIS data 2000-2013.

Figure 4. Disturbance frequency of South Island per 463-m pixel, based on interpretation of MODIS data 2000-2013.

Figure 5. Multivariate relationships between major water quality variables (median value for each site) and land use variables. For each plot, the primary explanatory variable from the stepwise regression (Table 8) is the x-axis, with bubble color representing the secondary explanatory variable. Note that oxidized nitrogen (NO_x) did not have a secondary explanatory variable. Selected catchments discussed in the text are labeled.

Figure 6. River water quality classes for upland (A) and lowland (B) catchments in New Zealand: I. clean river with high visual water clarity (CLAR) and low dissolved inorganic nutrients (DIN); II. sediment-impacted river with low CLAR and low DIN; III. nutrient-impacted river with high CLAR and high DIN; and IV. sediment- and nutrient-impacted river with low CLAR and high DIN. Classes are organized by ANZECC (2000) trigger values for water clarity (x-axis) and NO_x (y-axis). Catchments that exceed ANZECC guidelines for DRP are indicated in by grey-filled markers. Arrows indicate direction of trend over the 26 years inclusive from 1989 if significant (dashed) or meaningful (solid). No arrow means the trend was not significant.