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LETTER

Response lags and environmental dynamics of restoration efforts for Lake Rotorua, New Zealand

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Abstract

Regulatory responses to degradation of freshwater ecosystems have been characterized by long response times and have often failed to prevent declining health or to implement successful restoration programs. We studied environmental and management dynamics of ecosystem restoration in Lake Rotorua, New Zealand, where land use intensification is the main driver of water quality decline. Water quality decline, invasions by exotic submerged plants and occurrences of algal blooms have led to a number of in-lake interventions such as herbicide spraying (to control submerged plants) and dosing of inflows with Alum to flocculate phosphorus (and reduce algal blooms). Management of land use to reduce nutrient run-off has also been initiated. Based on the drivers-pressures-state-impact-response (DPSIR) framework, water quality changes and management responses were examined by studying research publications and data from 1922 to 2013. Multinomial regression analysis based on the generalized maximum entropy model was used to investigate the five categories of DPSIR and examine relationships of environmental dynamics and regulatory responses. We tested whether the visibility of ecosystem degradation in the public sphere, and social lag times to respond to them, were drivers of failures of these regulatory responses. Our study shows that management was reactive, and regulations often took effect only when ecosystem decline was already well advanced. There was a disconnect between land use intensification and its role in driving water quality change. Our results indicate that science can better inform management decision making by providing a holistic framework integrating ecological knowledge, economic interest and societal constraints.

1. Introduction

There is growing concern globally about degradation in the health of freshwater ecosystems (Dudgeon *et al* 2006, Vörösmarty *et al* 2010). Despite a high dependency on freshwater for the provision of a range of ecosystem services, governments globally have often failed to protect, and struggled to restore, freshwater resources, including rivers, streams, lakes and wetlands (Palmer and Richardson 2009, Moss 2010). In freshwater systems in particular, pressures from human activity have led to profound changes in ecosystem integrity and resilience (Dudgeon *et al* 2006, Folke 2006, Strayer and Dudgeon 2010). Management responses have often been insufficient or slow to mitigate these effects and at times ecological changes pass a threshold where they are difficult to reverse (Carpenter and Brock 1999, Scheffer and Carpenter 2003). In many cases, freshwater management is reactive rather than proactive (Carpenter *et al* 1998, Smith 2003), and mitigation of anthropogenic impacts on ecosystems is inherently complex, expensive, and subject to many uncertainties (Jeppesen *et al* 2003, Schindler 2012).

Inability to fully integrate ecological processes with management actions has been identified as contributing to flawed decision-making processes for freshwater management (Moss 1999). Whilst some studies of human impacts on ecosystems have considered an integrated ecological management approach and socio-economic aspects (Carpenter *et al* 1999, Atkins *et al* 2011, Pinto *et al* 2013), socio-economics and management actions have not necessarily been measured and quantified. Statistical analysis is not commonly incorporated into ecosystem management studies (e.g. Ellison 1996, McCann *et al* 2006). Ability to quantify outcomes from integrated management pathways based on ecological principles could address this constraint. Combining qualitative with quantitative research could lead to demonstrable impacts on ecological, socio-economic and management systems.

The drivers-pressures-state-impact-response (DPSIR) model is used to analyze resource management processes and inform decision-making in the policy process (De Groot *et al* 2010, Atkins *et al* 2011, Pinto *et al* 2013). The framework is widely applied in ecological research to manage diverse aquatic and terrestrial ecosystems, from local to global scales (Tscherning *et al* 2012). Within DPSIR, the dynamics of change can be viewed as linear or cyclical processes in the context of water management, as described by Carpenter *et al* (1998). The process starts with *drivers* referring to human activities responsible for changes in ecosystems. These exert *pressures,* which are processes leading to environmental change. The middle step describes the *state* of the ecosystem. A change of the state then has an *impact* in terms of effects on ecological processes and the human population. Lastly, *response* refers to how the human activities are managed to prevent adverse impacts.

The primary objective of this paper is to ascertain which factors were driving research focus with regards to the five categories of the DPSIR framework, using a case study of an iconic lake in New Zealand. Historical data for Lake Rotorua (North Island, New Zealand) from 1922 to 2013 have been used to provide a quantitative analysis of management responses. Publications are here used as a proxy to represent environmental changes and management dynamics. Other options could include environmental research funding or regulatory documents. Publications were chosen as they were easily quantifiable, could be categorized into the DPSIR framework, and were available for most years of the study period.

Water quality problems in Lake Rotorua have been linked to changes in land use and are characterized by long lag times (Fish 1969, Howard-Williams *et al* 1986, Abell *et al* 2011). We test the hypotheses that management responses to ecosystem degradation are linked to the visibility of ecosystem degradation in the public sphere; that social lag times can slow down such management responses; and that management strategies are reactive rather than proactively preventing ecosystem decline, and prone to fail to address the underlying causes for environmental degradation. We examine the intersecting elements of social lag times and poor visibility of environmental change that have affected the management of the lake historically, and how contemporary restoration approaches will need to avoid these elements. Our approach was to use general maximum entropy (GME) regression to analyze collected data. This multinomial method is suitable for the analysis of small datasets of continuous and binary variables, even when correlations between explanatory variables are present (Golan *et al* 1996).

2. Methods

To identify mechanisms causing failures to prevent lake ecosystem degradation, environmental changes and management-response barriers to the restoration of Lake Rotorua were analyzed. Data on historical changes of ecological health and management of the study lake were collected. Research publications were used as the best available proxy representing knowledge of environmental change and management responses. The DPSIR framework (Atkins *et al* 2011) was applied to the case study. Multinomial logistic regression analysis based on the GME model (Golan *et al* 1996) was used to study the effect that water quality and important management changes have had in stimulating studies in each variable category. Binary explanatory variables were included to explore the significance of relevant regulatory and institutional events. We identified significant trends and evaluated the usefulness of the DPSIR framework.

2.1. Study site

The Te Arawa lakes in the Central Volcanic Plateau, North Island, New Zealand, comprise 12 lakes of volcanic origin with varying characteristics and ranging in trophic state from oligotrophic to hypertrophic (Burns *et al* 2005, Scholes 2011). The largest lake, Lake Rotorua (figure 1), is the subject of this study. Its mean depth is 10 m and maximum depth is 45 m. It is presently classified as eutrophic. The original dominant land cover for this lakes region was temperate rainforest (Clarkson *et al* 1991). Soon after European settlement in the 1880s, bush and forest were cleared and farming became widely established. Ownership of the lake was taken from the Te Arawa tribe by the Crown in 1922 and returned in 2006.

The change in land use led to water quality problems that were first recognized in the 1920s (Phillips and Grigg 1922, Stafford and Rotorua District 1988). More intensive water quality research commenced in the 1960s (Hellaby 1960, Annett 1961, Fish 1963), at which point water quality had been severely compromised in the lake. The catchment was subject to increasing pastoral conversion and intensification during this time and in subsequent years. Proliferations of exotic submerged weeds were noted at the beginning of the 1960s (Annett 1961). Aerial spraying of weeds with Diquat® commenced in 1966, but did

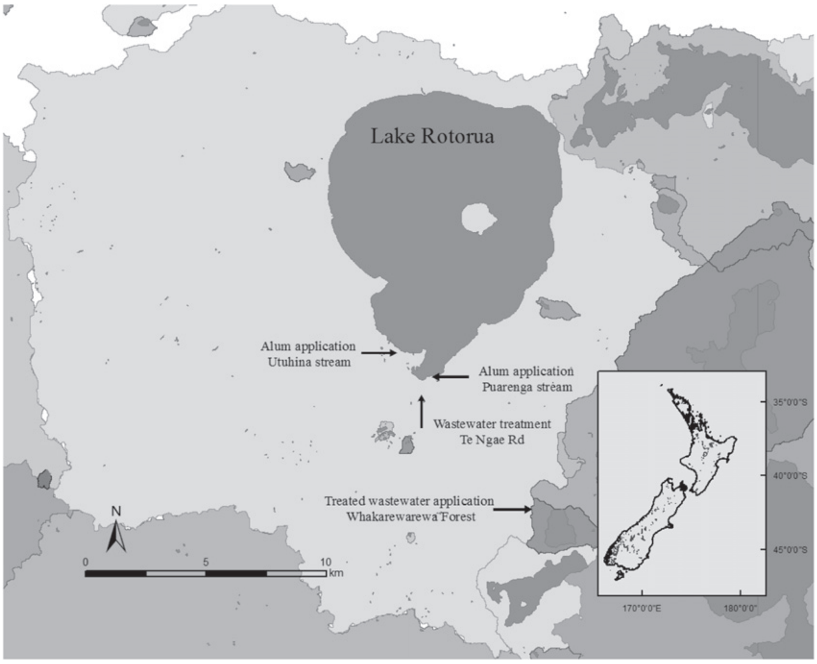

Figure 1. Catchment of Lake Rotorua, North Island, New Zealand. Arrows indicate streams for Alum application and land-based treated wastewater application.

Table 1. Overview of explanatory variables and description.

Variable name	Year	Description
TLI	1922–2013	Representation of water quality by trophic level index which includes measurements of total phosphorus, total nitrogen, and chlorophyll *a* concentrations and Secchi depth
Peer review	1922–2013	Indication of whether publication was subject to peer review
Lake Weed Society	1961	Formation of society working to improve water quality, founded after occurrence of major lake weed problems at Lake Rotorua
Kaituna catchment	1975	Upper Kaituna catchment control scheme to promote soil conservation and further to control lake levels including flood protection stopbanks and planting of riparian margins
FORLD	1980	Future options for the Rotorua Lake District, project formed to deal with land use and water quality issues, developing more sustainable resource use and alternative management options for the Rotorua lakes, including Lake Rotorua
RMA	1991	Resource Management Act; national level legislation promoting the sustainable management of natural resources, including water
Sewage	1991	Rotorua sewage treatment plant upgrade and diversion of treated waste water away from lake to land
Fonterra	2001	Formation of Fonterra Co-operative Group; large dairy marketing and processing co-operative, including more than 12 000 dairy farmers
EBOP Chair	2002	Bay of Plenty Regional Council Chair in Lake Restoration, based at the University of Waikato, to promote better management and monitoring of water quality within the Rotorua lakes
Cyano blooms	2003	Major blooms of cyanobacteria (e.g. *Anabaena planktonica*) in Lake Rotorua
Lake Settlement	2006	After being seized by the Crown in 1922, ownership of Lake Rotorua (lakebed) was returned to Te Arawa through signature of a deed of settlement
Rule 11	2008	Regional Water and Land Plan. First regional legislation affecting land management of the catchment of selected Rotorua lakes, aimed at controlling land use intensification, in particular nutrient (nitrogen) run-off from farms

little to address underlying causes of water quality decline (Stafford and Rotorua District 1988). Discharge of treated wastewater from the adjacent city of Rotorua (population c. 50 000) into Lake Rotorua ceased in 1991, when a tertiary-treatment land application commenced. This reduced nutrient loads, but after some improvement in water quality in the 1990s (Rutherford *et al* 1996), the quality continued to decline (Burger *et al* 2008). For an overview of changes in Lake Rotorua, selected water quality parameters measured over the last decades are given in supplementary S3.

The first step towards regulating nutrient inputs to restore the eutrophic lake to its pre-1960s levels was taken in 2002 by proposing a nutrient loss limit for the catchment (Rule 11; table 1). Alum dosing of the

Utuhina Stream inflow to Lake Rotorua commenced in 2006 and was extended to include the Puarenga Stream inflow in 2009. The objective was to flocculate phosphorus (P) in the streams, reduce P loads to the lake and limit algal growth in the lake. Currently, a regulated cap on the catchment nitrogen load is intended to reduce nitrogen loads from the catchment by around 40% by 2030. Following Alum dosing, water quality has recently improved and in 2012 met the target consistent with 1960s water quality levels for the first time (BOPRC 2013).

2.2. Data collection

We collected published data on water quality and ecosystem health of Lake Rotorua using database searches. A primary data source was a comprehensive bibliography covering years 1922–2002 (Miller 2003). A keyword search of Google Scholar, ISI Web of Science and NZ Science was conducted to expand and complement this dataset. Keywords used were 'eutrophication', 'water quality', 'nutrient*' and 'Lake Rotorua'. Data collection yielded a list of published documents addressing water quality issues for the lake from 1922 to 2013 (supplementary S1). Each publication was assigned to one of the five categories of the DPSIR framework, according to the primary focus of the paper. The focus was determined through scanning of the text where possible; where the text was not accessible, abstracts and titles were used to choose the category the document primarily addresses (see category description in introduction). Publications that covered more than one category were counted in the category that corresponded with their predominant focus. A total of 351 publications was collected and categorized.

2.3. Regression analysis

The dependent variable of the regression analysis consisted of a multinomial response, denoting whether a study focused on *drivers*, *pressures*, *state*, *impact* or *response*. A range of explanatory variables was incorporated. The regression analysis was applied to the 351 publications to investigate which factors (table 1) had the greatest impact on the probability that a publication belonged to one of the five different categories of the dependent variable.

One explanatory variable in the regression reflected water quality. Each publication was assigned a value for water quality as indicated by the trophic level index (TLI) observed at time of publication. TLI, similar to the trophic state index (Carlson and Simpson 1996), gives an assessment of the trophic state of a lake and is widely used in New Zealand as an integrative proxy for water quality (e.g. Verburg *et al* 2010). The index includes measurements of total phosphorus, total nitrogen and chlorophyll *a* concentrations and Secchi depth (Burns *et al* 1999). TLI levels range from 0.0 (ultra-microtrophic) to 7.0 (hypertrophic). A eutrophic condition is denoted by a TLI level of 4.0–5.0. TLI is calculated using equations relating to the four variables:

$$\text{Chlorophyll } a \text{ TLc} = 2.22 + 2.54 \log(\text{Chl}a), \tag{1}$$

$$\text{Secchi depth TLs} = 5.10 + 2.60 \log(1/\text{SD} - 1/40), \tag{2}$$

$$\text{Total phosphorus TLp} = 0.218 + 2.92 \log(\text{TP}), \tag{3}$$

$$\text{Total nitrogen TLn} = -3.61 + 3.01 \log(\text{TN}), \tag{4}$$

$$\text{Integrated value TLI} = 1/4(\text{TLc} + \text{TLs} + \text{TLp} + \text{TLn}). \tag{5}$$

TLI was calculated using measured data provided by Bay of Plenty Regional Council and the National Institute for Water and Atmospheric Research (NIWA), based on samples taken routinely in the central region of the lake. Prior to commencement of measurement, TLI levels between 1922 and 1966 were interpolated under the assumption of a linear increase from a modeled TLI of 4.04 for the 1920s (Hamilton *et al* 2012). While earlier TLI levels are likely to have fluctuated, as measurements of later years show, this linear increase is expected to at least represent the trend of a continuous decline in water quality over those years.

Eleven binary explanatory variables were used to analyze dynamics in water quality research, management and environmental change. One variable indicated whether or not the publication was peer reviewed. Ten further variables were chosen as indicators of regulatory developments, environmental changes, or changes in institutions and science. Explanatory variables are listed in table 1; a statistical overview is given in table 2. The regression analysis used a GME model based on a method developed by Golan *et al* (1996). Equations used for this calculation are given in table 3. Entropy refers to measures of uncertainty in a variable, making it possible to recover information about systems with incomplete response data. GME is based on a linear regression problem where probabilities are calculated though nonlinear optimization. The maximization of the entropy equation (table 3) identifies the probabilities that could have been generated by the data in the most number of ways. The regression problem is solved using nonlinear optimization code, more specifically the general algebraic modeling system (GAMS) (Brooke *et al* 2014).

Results from the regression analysis yield an odds ratio, as well as a measure of statistical significance (p value) for each of the explanatory variables. The odds ratio shows how strongly one property or outcome, corresponding to the categories of the dependent variable, is associated with the presence of another

Table 2. Summary of statistical information of explanatory variables.

Variable	Type	Mean	Std dev	Min	Max
TLI	Continuous	4.55	0.25	4.04	5.06
Lake Weed Society (1961)	Binary	0.98	0.15	0.00	1.00
Kaituna catchment (1975)	Binary	0.81	0.39	0.00	1.00
FORLD (1980)	Binary	0.64	0.48	0.00	1.00
RMA (1991)	Binary	0.46	0.50	0.00	1.00
Sewage (1991)	Binary	0.46	0.50	0.00	1.00
Fonterra (2001)	Binary	0.33	0.47	0.00	1.00
EBOP chair (2002)	Binary	0.30	0.46	0.00	1.00
Cyano blooms (2003)	Binary	0.28	0.45	0.00	1.00
Lake Settlement (2006)	Binary	0.22	0.42	0.00	1.00
Rule 11 (2008)	Binary	0.17	0.38	0.00	1.00
Peer review	Binary	0.33	0.47	0.00	1.00

property in a dataset. A coefficient for each explanatory variable shows the probability that publications focused on one of the categories of the dependent variable, compared to a baseline category. The *state* category from the DPSIR framework was chosen as the baseline category for the calculation of odds ratios. This was chosen for simplicity, because it is intermediate in the DPSIR series, and because this classification contained the highest number of observations.

2.4. Temporal resolution analysis

Time series analysis was used to analyze temporal resolution of the DPSIR framework and to quantify the lags between the DPSIR categories and the explanatory variables of the multinomial regression. For the analysis, a Pearson correlation coefficient r was calculated for each of the binary explanatory variables (except peer review, which is not linked to a particular year) relating to each of the categories of the DPSIR framework, using the equation

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\left\{n\sum x^2 - \left(\sum x\right)^2\right\}\left\{n\sum y^2 - \left(\sum y\right)^2\right\}},$$

where n is the number of pairs, x is the number of x scores (year of publication) and y is the number of y scores (number of publications). Coefficients were calculated for time lag series of 3, 5 and 10 years time lag after the year of each explanatory variable. To test statistical significance, the p value for each correlation coefficient was also calculated.

3. Results

3.1. Water quality research and data

All documents were categorized according to their primary focus within the DPSIR framework. Forty-seven publications were categorized in the *drivers* category, 75 in the *pressures* category, 116 in the *state* category, 20 in the *impact* category, and 93 in the *response* category (supplementary S1). A timeline of environmental change, management responses and other important events represented by the binary explanatory variables is plotted in figure 2. Results of the data collection, including water quality (TLI) and number of publications, are also given in figure 2. A decline in water quality (i.e., an increase in TLI) is indicated by a steady move towards a TLI of 5.0 in the 1970s, with further peaks in TLI levels observed in 1985 (5.06) and 2003 (5.03). Publication numbers reached a first peak at a similar time (early 1970s), dropped off in the 1980s and a second peak occurred in the late 1990s and early 2000s.

There was a substantial increase in research soon after 1960 when water quality problems first started to become obvious to the public, with a peak in 1975 (total of 22). When visibility of eutrophication subsided after initial management responses, such as physical removal and aerial spraying of weeds, the number of publications decreased. Recent times saw consistently higher numbers of publications after 2003, when algal blooms again became prevalent on Lake Rotorua (Burger *et al* 2007).

Times of visible water quality changes led to responses in management to address the changes after some lag time of five to ten years (figure 2). Lake weed occurrences in the 1960s were followed by the Kaituna catchment scheme in 1975, while cyanobacterial blooms in the 2000s were followed by Rule 11 in 2008. High trophic levels in mid-1980s were also followed by the sewage upgrade scheme in 1991 (figure 2). Water quality of Lake Rotorua has fluctuated over the years, but a continuous trend of degradation resulted in these management responses, while initially lagging in efficiency in terms of significant improvements in water quality. Only since 2006 has water quality continuously improved (figure 2), suggesting that interventions until then were at best partially successful in addressing water quality issues, allowing degradation to continue.

3.2. GME regression analysis

Water quality (TLI) had a significant relationship ($p < 0.05$) with the category of publications (table 4), with a shift in focus of publications to the *impact* category, relative to the *state* category. Occurrences of

Table 3. Generalized maximum entropy regression equation and description.

Equation	Formula	Description		Constraints
Coefficient estimator	$\beta_k = \sum_{c=1}^{C} P_{k,c} z_{k,c} \quad \forall\ k$	β_k	Regression coefficient	$P_{k,c} \in [0,\ 1]$ and $\sum_{c=1}^{C} P_{k,c} z_{k,c} = 1 \quad \forall\ k$
		$P_{k,c}$	Decision variables	
		$z_{k,c}$	Fixed supports	
		$c = [1,\ 2,\ \ldots,\ C]$	Support points index	
Error term	$e_t = \sum_{d=1}^{D} W_{t,d} v_{t,d}\ \forall\ t$	$W_{t,d}$	Decision variables	$W_{t,d} \in [0,\ 1] W_{t,d}$ and $\sum_{d=1}^{D} W_{t,d} = 1$
		$v_{t,d}$	Fixed supports	
		$d = [1,\ 2,\ \ldots,\ D]$	Support points index	
Data equation	$y_t = \sum_{k=1}^{K} \beta_k X_{k,t} + e_t = \sum_{k=1}^{K} \sum_{c=1}^{C} P_{k,c} z_{k,c} X_{k,t}$	$X_{k,t}$	Parameter data	
	$+ \sum_{d=1}^{D} W_{t,d} v_{t,d} \quad \forall\ t$	$k = 1,\ 2,\ \ldots,\ K$	Over N observations	
Entropy equation	$\max J = -\sum_{k=1}^{K} \sum_{c=1}^{C} P_{k,c}\ ln\left(P_{k,c}\right) - \sum_{t=1}^{T} \sum_{d=1}^{D} W_{t,d}\ ln\left(W_{t,d}\right)$	Objective function: maximization of the entropy criterion		$W_{t,d} \geqslant 0$ $P_{k,c} \geqslant 0$ $\sum_{c=1}^{C} P_{k,c} z_{k,c} = 1$ $\sum_{d=1}^{D} W_{t,d} = 1$

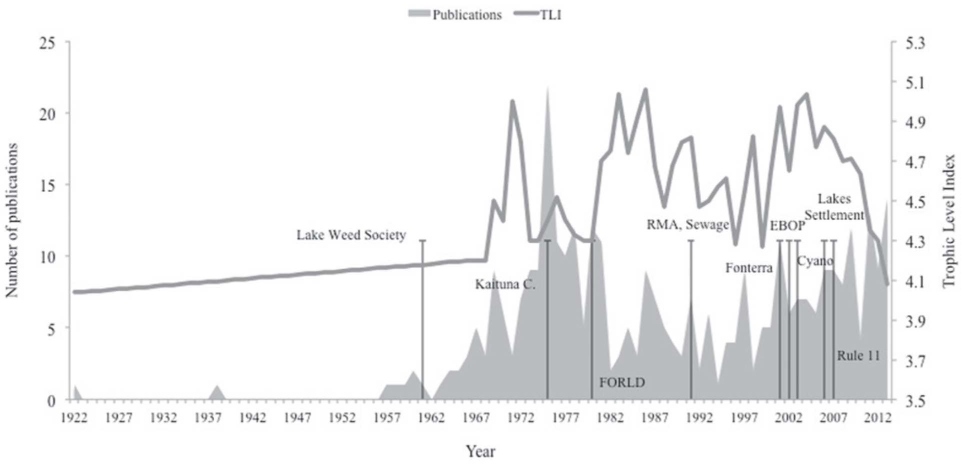

Figure 2. Water quality of Lake Rotorua and related publications for Lake Rotorua, 1922–2013. Explanatory variables are marked in year of occurrence.

Table 4. Results of GME regression analysis presenting odds ratios of explanatory variables. Asterisks indicate statistical significance (* = statistical at 10% level, ** = significant at 5% level, *** = significant at 1% level).

Explanatory variable	Type	p value	Drivers	Pressures	Impact	Response
Trophic level	Continuous	<0.05**	1.28	1.71	8.98	1.99
Lake Weed Society (1961)	Binary	<0.05**	1.51	1.51	58.83	1.51
Kaituna catchment (1975)	Binary	<0.05**	0.84	0.68	1.83	0.38
FORLD (1980)	Binary	>0.05	1.88	4.36	0.53	5.82
RMA (1991)	Binary	>0.05	0.46	0.04	8.09	0.74
Sewage (1991)	Binary	<0.01***	1.78	3	0.89	0.94
Fonterra (2001)	Binary	<0.05**	0	0	0.95	0.74
EBOP chair (2002)	Binary	<0.05**	56.95	51.71	0	1
Cyano blooms (2003)	Binary	<0.05**	0.76	3.06	73.2	3.34
Lake Settlement (2006)	Binary	>0.1	2.66	0.6	3.39	0.14
Rule 11 (2008)	Binary	<0.05**	7.93	1.39	1.7	3.27
Peer review	Binary	>0.05	0.34	0.74	0.96	0.27
Count R^2	54.4%					

cyanobacterial blooms in 2003 also had a statistically-significant impact on the categorical focus of publications ($p < 0.05$), and led to a noticeable shift in focus to the *impact* category, with odds being 73.2 times higher that a publication was focused on *impact*, relative to the *state*. A further statistically-significant effect ($p < 0.05$) was the formation of the Lake Weed Society, which occurred following major lake weed problems in the 1960s. The Society associated with this variable had a significant impact in terms of changing the focus of publications, indicated by odds of 58.8 times higher for *impact* relative to *state*.

The variable with the least statistical significance ($p > 0.1$) was Lake Settlement. The introduction of the Resource Management Act (1991) and the Future Options for the Rotorua Lakes (FORLD) project also had no statistical significance ($p > 0.05$). The formation of the Fonterra dairy cooperative in 2001 and the Kaituna catchment scheme (1975) had no significant impact on the categorical focus of publications, indicated by low odds ratios. Contrary, the appointment of a University of Waikato-based Chair in Lake Restoration (2002) and the implementation of Rule 11 as a regulatory step aimed at managing land use for improvement of water quality in 2008 were of significance ($p < 0.05$). Rule 11 had an impact in changing the focus of the publications to the *drivers* category, indicated by odds of 7.93 times higher relative to *state*. Odds for the response category were 3.27 times higher. The Lakes Chair appointment had an impact in changing the focus to the *drivers* (odds 57.0 times higher) and *pressures* (51.7) categories, relative to the *state* category.

The variable associated with removal of point source pollution through sewage treatment upgrades (1991) had the highest statistical significance ($p < 0.01$), with odds ratios that indicated a shift in focus towards the *pressures* category, with odds three times higher relative to the *state*. The peer review variable showed no statistical significance ($p > 0.05$) and low odds ratio (<1), indicating that this variable had no impact on the categorical focus of publications. Our results show that water quality levels, visible water quality changes (algal blooms) and public campaigns

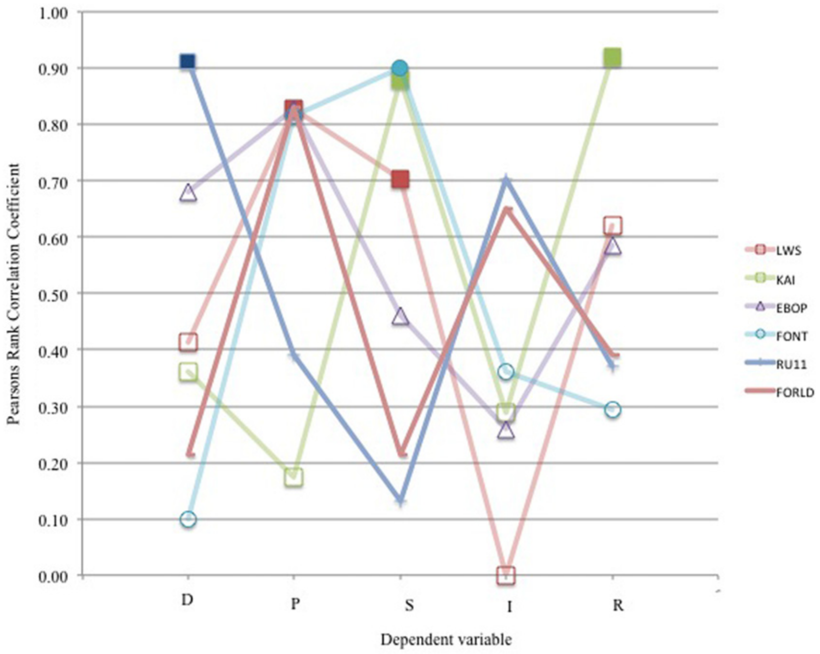

Figure 3. Explanatory variables that exhibited statistically significant relationship; plot shows the correlation coefficient for each dependent variable (*D*, *P*, *S*, *I*, *R*) for a five-year time lag.

were most significant in determining the focus of water quality research, which is shown by the high statistical significance and odds ratios of the explanatory variables most closely linked to this (water quality indicated by TLI, cyano blooms, Lake Weed Society, EBOP chair and Rule 11) (table 4).

3.3. Temporal resolution analysis

Results of the time lag analysis show the temporal resolution of the DPSIR framework and the explanatory variables. A time lag of five years after each year associated with occurrence of the explanatory variables was identified as the most significant time step. A three-year lag showed some significance, while a ten-year lag showed little statistical significance (supplementary S2). The most significant explanatory variables after the five-year lag included FORLD, Rule 11, EBOP chair and Lake Weed Society. The *pressures* category showed most statistically significant correlations, whereas the *impact* category showed low significance (figure 3). RMA and Sewage showed weak correlations after three years only. After five years, correlations were strongest for EBOP chair, Lake Weed Society, Fonterra and FORLD for the *pressures* category. Fonterra and Kaituna catchment show strong correlation with the *state* category. The Lake Settlement variable showed no statistically significant correlations, with the highest (<0.65) correlation coefficients occurring after a five-year lag time. After ten years, the only significant correlations are Cyano blooms related to the *drivers* category, and Lake Weed Society to the *state* category (supplementary S2).

4. Discussion

This study is the first to integrate GME regression with the DPSIR framework. With this integration we have demonstrated a novel means to analyze trends in published research on lake restoration and water quality in the study area. In the following we address how poor visibility of environmental change, social lag times from recognition of degradation to management responses, and a reactive nature of management responses contribute significantly to failures in restorative lake management.

4.1. Visibility of environmental degradation

In this case study, immediately visible events such as the occurrence of extensive lake weed problems (‘Lake Weed Society’) and, decades later, algal blooms (‘cyano blooms’), were most significant in influencing publication numbers and type (table 4). While variables associated with visible environmental change (e.g. water quality, algal blooms) had a significant impact and shifted the publications’ focus towards the *impact* category (associated with a transition to management responses), other variables not so visible to the public had little impact (e.g. RMA, FORLD). TLI, the formation of the Lake Weed Society, and major lake weed growth and algal blooms commencing in 2003 had a major impact on shifting the focus to the *impact* category. Cyano blooms and Lake Weed Society also were the only variables showing significance in the 10 year timeframe in the correlation analysis, indicating that these events perhaps had a lasting impact.

These events had an immediate negative impact on the public, including visual effects, lake closures or health warnings, which can function as a motivation for both research conducted and management responses taken (table 4). The variable of *impact* appears important to drive change, as publications within this category focus on the direct impact that degradation has on the public. This variable is not strongly populated in the dataset of publications, with only 20 out of 351. The *impact* category was also of little significance in the temporal resolution analysis. Minimal focus on the impact that water quality issues have on the public may also explain a lack of regulation that could improve management.

4.2. Response lag times

Response lag times are related to the time between the recognition of the degradation process of an ecosystem and ensuing management responses. Slow management, political will and the research funding might all play a role in causing these lags. In our case study, this refers to time passing between recognition of environmental change in research and public discussion, including the formation of the Lake Weed Society in the 1960s, and the first attempts to address water quality issues through nutrient load management starting in 1975, up to 15 years later (Kaituna catchment scheme), followed by further changes in 1991 (sewage upgrade). Formal regulation was not implemented until the 2008 (Rule 11); almost fifty years after lake water quality problems were first noticed.

Our temporal resolution analysis shows lag times between events represented by the explanatory variables and responses within the DPSIR categories are most significant at five years. This might be associated with the nature of the scientific process, which can contribute lag times through peer-review processes and dependence on research funding availability, which is also influenced by political factors. In our study, there was no significance to whether a study was peer-reviewed or not, which suggests that the approach of studying publications is a valid approximation. Peer-reviewed publications often appear to take longer to be published, but results here indicate that a time lag of five years occurred in all publications, and was a significant temporal effect whereas the type of publication was not significant (table 4, supplementary S2).

Lag times result in separation of recognition of an environmental problem in the scientific community from regulation formulated to counter the problem. These lags are particularly evident in our study in the number of publications focused on water quality, lake ecosystem degradation and its causes in the 1970s (total $n = 94$) (figure 2). Sound knowledge of how water quality decline was linked to land use was established at that time (Fish 1969), but no regulation was implemented to address land use intensification until 2002 (Rule 11). Lags are also visible at a national scale, where freshwater ecosystem decline was in many cases allowed to continue with insufficient regulation (PCE 2013). Up to five decades between recognition of causes of environmental degradation and responses led to further degradation of the ecosystems.

4.3. Reactive management responses

As water quality decline was allowed to progress when knowledge of degradation and its causes already existed, responses tended to be reactive. Responses were often only implemented at a stage of severe, visible environmental degradation in the form of weed growth and algal blooms. Reactive management is common internationally, and often regulations take effect only when ecosystem decline has already progressed significantly, potentially leading to regime shifts and widespread algal blooms (figure 2; Scheffer and Carpenter 2003, Smith 2003). At that point, management to prevent further degradation may be difficult due to established land use activities, nutrients already in the lake, regime shifts that may be difficult to reverse (Scheffer and Carpenter 2003), and additional nutrients already in transit due to long groundwater lags (Morgenstern and Gordon 2006, Burger *et al* 2008).

Regulation allowed for continuation of land use intensification, in particular dairying, in the catchments of several Rotorua lakes (Timmins and Savage 1981, Edgar 2008). As dairying is now firmly established as an industry important to the regional economy, the costs of restoring lakes have to date been borne by the entire rate-paying community through regional council funded initiatives to restore water quality, rather than directing some of the cost to those land uses that have caused the decline. Many agricultural stakeholders favor intensification of land use, which is at odds with lake restoration goals (Abell *et al* 2011). The disconnect between land use impacts and lake ecosystem change means ecosystem degradation is unnoticed by the public until a threshold consistent with observable deterioration is reached, such as levels of eutrophication at which blooms of algae are widespread. Within the concept of regime shift, this may coincide with the point where ecosystem degradation has progressed far enough to make restoration more difficult and costly (Scheffer and Carpenter 2003).

4.4. Applicability of the DPSIR framework

Our results also indicate that the DPSIR framework might not be entirely suitable to describe the process of environmental degradation and its management responses. The concept assumes a linear progression from one category to the next, culminating in a management response. However, our analysis shows that such linear progression might not always take place. Our correlation coefficient analysis shows that there is no temporal progression through the categories of the DPSIR framework (figure 3, supplementary S2).

Odds ratios and statistical fit of the model derived from the multinomial regression analysis give insight into the relevance of the DPSIR framework as applied in this context. The fit of the model, illustrated by the count R^2 (54.4%, table 4), is comparable to that obtained in other cross-sectional studies that employ entropy regression for analysis of datasets of this kind (e.g. Doole *et al* 2014). This result indicated the adequacy of the method and estimates obtained.

Some variables were expected to have a more significant impact, including trophic level and cyanobacterial blooms, when compared to the sewage treatment upgrade, which showed the highest statistical significance, even though odds ratios were comparatively lower. The 'peer review' and 'Fonterra' variables were expected to be of low significance. Both variables are not at the forefront of public awareness of environmental change, and were also expected to be of little relevance to research conducted. The RMA as a major piece of natural resource legislation in New Zealand was expected to be of at least some significance. Authorities perhaps needed time to become familiar with implementing this legislation within the intended context, leading to additional lag time.

4.5. Wider implications of research

The approach of using research publications to represent knowledge of environmental changes and management responses is limited; there are many other factors influencing these publications, including research funding, research employment numbers and the general political and socio-economic climate within a region or country. The science process itself has a significant impact on the number, type and focus of publications in this area. Scientific research processes are complex and (often commercially driven) funding available plays a major role in this (Edmeades 2004). However, we found this approach nevertheless provided useful insights into the dynamics studied, and provided the best proxy available for our study.

Our study site is ideally suited to studying regulatory failure arising from long lags between recognition and action in the field of natural resource management. Natural resource regulators of Lake Rotorua were slow to recognize scientific insights into water quality issues caused by land use intensification, and changes have taken place only very recently. These hindrances are applicable to a wider spatial scale, when evaluating how resources are managed globally and how ecosystems are exploited to a point where change becomes difficult to reverse. Business-as-usual is the pathway that generally encourages further ecosystem degradation until a threshold is reached where the public is affected significantly, and governments accept the need to drive change.

A focus on economic development means freshwater management is subject to a trade-off between economic benefits and environmental costs, which creates a barrier to improvements in water quality (Edgar 2008, PCE 2013). Focus on economic aspects is often assumed as the underlying reason why ecosystem health is not prioritized (Scheffer *et al* 2000, Marsh 2012). This appears to be only one aspect of the failure to maintain or restore the health of ecosystems. Even when the protection of waterways provides economic gain, management can still be prone to failure as social lag times and the lack of visibility of environmental issues lead to inaction and complacency. Reasons for the failure to protect lakes from degradation from land use change therefore appear to include long social lags, and a lack of visibility of environmental problems, alongside the unquantified aspect that some land use changes have significant economic implications. For more effective ways of managing lakes and land use, and informing regulation under given environmental and socio-economic constraints, an integrated approach needs to be taken that considers these constraints.

5. Conclusion

This paper provides a quantitative evaluation of how management responses are reactive and what drove failures of lake ecosystem protection and restoration. It explores how knowledge of these dynamics can be integrated into more effective management aimed at reducing human impacts such as pollution and nutrient runoff into waterways. The aim of this novel approach is not wide-scale reduction of environmental impacts compromising socio-economic aspects; rather it is supporting a new framework of policy design where existing shortcomings can be resolved by an integrative, interdisciplinary approach. This encompasses ecological knowledge, economic interests and societal constraints. Simulation and models could help visualize environmental problems, and inform decisions of policy makers. Sustainable resource management could benefit from a combination of sound scientific knowledge, educated communities and collaborative approaches to regulation that account for all stakeholders' interests.

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