The Australian Journal of
Agricultural and
Resource Economics

AARES
AUSTRALASIAN AGRICULTURAL & RESOURCE ECONOMICS SOCIETY

Australian Journal of Agricultural and Resource Economics, 63, pp. 354–382

The optimal diffusion of mitigation options for environmental management

Graeme J. Doole, Geoff Kaine and Zack Dorner[†]

A new direction for evaluating pollution policy is proposed, focused on optimal investment pathways for mitigation capital. The approach allows practitioners to draw directly from key principles in the diffusion literature. A two-stage, policy-development framework is introduced. The first stage consists of empirical modelling to assess optimal diffusion pathways for diverse mitigation options. The second involves determining the relative strengths of different policy actions to address diffusion rates or maximum levels of adoption that diverge from optimal levels. The advantages of this new approach are demonstrated in an agri-environmental context, concerning the off-site impacts of intensive agriculture on water quality. The viewpoint provided by the novel approach establishes the importance of adoptability – alongside the traditional measures of abatement effectiveness and cost – for mitigation practices in policy assessment. The key role that durable mitigation capital plays in addressing dynamic externalities is demonstrated, alongside the importance of structured diffusion cascades for alternate mitigation options.

Key words: agri-environmental management, capital, diffusion, dynamic externality, policy approaches.

1. Introduction

Sustainable futures depend on the broadscale adoption of technologies or practices that help to satisfy the objectives of users, while also reducing off-site environmental impacts (Iver *et al*. 2015; iPES Food, 2016). Examples are the adoption of energy-efficient technologies to reduce greenhouse gas emissions from households (Caird *et al*. 2008) and the use of afforestation to mitigate soil erosion (Cacho 2001). Often, there is a broad mismatch between the net benefits accruing to private and public agents from the adoption of different mitigation options (Jaffe *et al*. 2004). Landholders generally have little to no financial incentive to consider the off-site or external costs of their actions across time (i.e. dynamic externalities). Low private gains consequently drive underinvestment in mitigation options, resulting in suboptimal social outcomes (Pannell *et al*. 2006, 2014). Further, a farmer is likely to have

[†] Graeme J. Doole (e-mail: graeme.doole@dairynz.co.nz) and Zack Dorner were with the School of Accounting, Finance, and Economics, University of Waikato, Hamilton, New Zealand and with the Ministry for the Environment, Wellington, New Zealand when this work was completed. Graeme J. Doole is at DairyNZ, Hamilton, New Zealand and the School of Agricultural and Resource Economics, University of Western Australia, Australia. Geoff Kaine is at the Landcare Research, Hamilton, New Zealand.

doi: 10.1111/1467-8489.12291

a higher private discount rate for investment in mitigation compared with the appropriate social discount rate. This difference has a range of underlying drivers, including the general discrepancy between the return on private investments and social/consumption rates of time preference (Arrow *et al.* 2014), market distortions from taxation (Brealey *et al.* 1997), imperfect land markets (McConnell 1983), risk attitudes, and short business tenure. Accordingly, human activity continues to accelerate the rate and scale of ecosystem degradation experienced at the global level (UNEP, 2012). In this context, the ultimate goal of environmental policy is to manipulate the incentives facing private agents across time, to move towards more favourable social outcomes (Pannell 2008).

The *diffusion* of an innovation is its level of adoption across a population after a certain period of time has elapsed (Feder and Umali 1993). Accordingly, the *diffusion rate* is the speed at which this diffusion occurs over time. Generally, an S-shaped (or sigmoidal) curve is used to describe the process of diffusion for new technologies across diverse contexts (Rogers 2003; Meade and Islam 2006). The main factors that determine diffusion rates are as follows: (i) heterogeneity in the perceived and real advantages of new practices, relative to current activities (relative advantage); (ii) a capacity to trial the innovation; (iii) the importance of social networks in influencing uptake; (iv) differences between potential users in terms of their innovativeness and risk preferences; and (v) ongoing institutional, market and technical changes (Rogers 2003; Pannell *et al.* 2006, 2014). However, a diffusion curve also represents benefits for users associated with a greater scale of implementation. These returns will typically arise from the accumulation of knowledge and experience, bandwagon effects and capacity for colearning (Park 1994; Costanza 2014).

Economists have placed much focus on managing environmental stocks, such as fish populations (Clark 2010) and soil depth (McConnell 1983). This classification is valuable because many important environmental resources are stocks and this fundamentally determines the way they respond to management. For example, stocks retain the effects of overexploitation for long periods, require persistent investment to reverse downward trends and introduce delays in system response (Maani and Cavana 2007). The importance of stock effects also emerges from several leading studies that have explored the optimal accumulation of mitigation efforts. Grepperud (1997) analysed optimal rates of accumulation for durable mitigation techniques (e.g. terraces) to reduce soil erosion rates, while Cacho *et al.* (2001) studied optimal investment rates for slow-growing forests that could help to reverse soil salinisation. High global interest in greenhouse-gas emissions has also led to research on optimal stock levels for adaptive capital, which reduces the impacts of climate change on productive activities (Felgenhauer and Webster 2014; Millner and Dietz 2015). These studies highlight the value of durable mitigation options for environmental improvement. Additionally, they demonstrate the close symmetry between investment rules for productive and mitigation capital stocks. This extends an earlier literature that highlights the economic importance of managing environmental stocks in ways that align with standard investment theory (McConnell 1983; Clark 2010). Nonetheless, this work does not consider the dynamics of diffusion.

The goal of this study was to describe a general framework for analysing the optimal management of dynamic externalities. It places a concerted focus on the diffusion pathways of durable mitigation capital and how to manipulate these with policy. This extends a rich literature that analyses the impacts of diffusion on competing firms (Gotz 2000), members of a diverse population (Caird *et al.* 2008), and along supply chains (Reardon *et al.* 2017). The framework focuses on the description and application of a two-stage process for policy development, consisting of: (i) a novel modelling approach; and (ii) a policy framework to help design pathways towards improved environmental outcomes. The paper makes several contributions. First, it contributes to theory by integrating diffusion principles with standard concepts considered in environmental management. Second, it contributes to methodology by introducing a new economic model of environmental management, which centres on the principles of diffusion and optimal investment in stocks of mitigation capital (Section 2). Third, it sets out a framework for designing policies (Section 3) to guide movement towards the optimal ceilings or rates of diffusion identified in the modelling stage. Fourth, a case study application focused on attaining community goals for water clarity in a New Zealand catchment demonstrates the practical value of the framework (Section 4). Last, the methodological and policy implications of the framework are discussed in Section 5.

2. A model of diffusion and environmental quality

This section presents an optimal-control model (Kamien and Schwartz 1991), while also providing some analytical insights. Section 4 provides more detailed insights through empirical analysis. Optimal control is a mathematical technique that allows a user to characterise the best way to manage a dynamic system, to optimise a suitable measure of performance.

The focus of the model is the diffusion rate of different mitigation options. A mitigation option in the context of this study is a technology or practice that reduces the loss of a contaminant from agricultural land. In the context of the case study, this represents a specific technology or practice that reduces sediment loss (Section 4). The model provides insight into the nature of socially optimal diffusion pathways for different mitigation options. Specific policy options to achieve this end are discussed in Section 3.

Key assumptions are applied to the mitigation options: (i) The effectiveness of each option for reducing contaminant loss remains static; (ii) No new mitigation options are developed across the time horizon; (iii) The adoption of mitigation options poses a net cost on producers over the time horizon; and (iv) Later adopters face a greater cost burden. (There is no second-mover advantage because no new mitigation options are assumed to be developed.)

These assumptions appear restrictive; yet, their level of abstraction aligns with standard practice in policy assessment, often due to scarce data and low project resourcing. These assumptions can be relaxed, and this remains a key area for further research.

Variables in the model are presented as capital letters. Capital letters presented as subscripts denote the derivative of a function with respect to that variable. Time notation is suppressed where it does not affect interpretation.

The model is defined across a time horizon that extends from the current time to an endpoint denoted T. That is, $t = [1,\ldots,T]$. A set of $i = [1,2,\ldots,I]$ individual mitigation options are defined.

The level of adoption observed for a given mitigation i is denoted $D_i(t)$. The state variable $D_i(t)$ is defined here as the proportion of the population that uses mitigation i at time t. It could be described alternatively as the total area or number of farms across which a mitigation is used.

The diffusion rate $[\dot{D}_i(t)]$ is the rate of change in the state variable (i.e. $\dot{D}_i(t) = d_{D_i}/dt$). It can either be positive through adoption, be negative through disadoption or zero if adoption and disadoption rates are equivalent. The level of adoption $[D_i(t)]$ is a stock variable, while the diffusion rate $[\dot{D}_i(t)]$ is a flow, in system dynamics terms (Maani and Cavana 2007).

The rate of diffusion is described through the equation:

$$\dot{D}_i = a_i(R_i, K_i, D_i) - l_i(D_i) - m_i(D_i) \text{ for all } i, \quad (1)$$

where a_i (R_i, K_i, D_i) is a function defining the diffusion rate without disadoption, $l_i(D_i)$ is the rate of disadoption arising from abandonment, and $m_i(D_i)$ is a reduction in the level of adoption arising from the depreciation of mitigation capital. Disadoption and depreciation are not control variables; rather, they enter the model as functions of the stock variable ($D_i(t)$). Disadoption is an increasing function of the level of adoption (i.e. $l_{D_i} > 0$). This relationship is justified by broader diffusion increasing the probability that the mitigation option is not appropriate to a specific farm context in the long term (Rogers 2003), social momentum leading to adoption despite the mitigation option having low private advantage (Golder and Tellis 2004) and longer time periods increasing the chance that external conditions (e.g. changes in input and output prices) alter the value proposition of the innovation (Neill and Lee 2001). Depreciation is an increasing function of the level of adoption (i.e. $m_{D_i} > 0$) too, since a higher capital stock implies a greater loss to depreciation, *ceteris paribus* (Grepperud 1997).

Depreciation represents a loss over time in the capacity of an asset to perform its intended function. This chiefly arises from physical deterioration and/or loss of relevance (obsolescence) (Baum 1991; Thomsen and van der Flier 2011). Economic depreciation is a standard inclusion in financial evaluation, helping to trace the decline in value of a capital asset. This assessment follows standard approaches in environmental economics (Charles 1983; Grepperud 1997), through discounting with a risk-free rate (Clark 2010) and representing depreciation as an annual decrease in the capital stock (e.g. see Eqn 1 above) (Grepperud 1997; Boucekkine *et al.* 2010). This approach is advantageous for several reasons. First, it improves clarity around capital-stock dynamics, allowing asset value to be traced across time. Second, it allows comparison with results from other studies, given its consistency with past work. Third, it focuses on the optimal investment path by balancing the current and future net benefits of capital accumulation (Kamien and Schwartz 1991), thereby exploiting the equivalency of standard capital theory and optimal-control methods (Dorfman 1969). Last, it separates the issues of depreciation and discounting, thereby providing greater clarity and accuracy. This aligns with similar recommendations to separate the impacts of risk and discounting (Moore *et al.* 2004).

Some authors utilise a different approach. This involves accounting for rates of asset growth and depreciation in the discount rate and excluding the cost of depreciation from the cost component of a cost-benefit analysis (Baum and MacGregor 1992; Deakin 1999). This discount rate can then be used as a hurdle, to which to compare the computed return for alternative investments without a full cost-benefit analysis taking place (Baum and MacGregor 1992). In contrast, it can also generate a richer specification of the discount rate in a standard evaluation (Deakin 1999). These approaches have highlighted the value of better integration between property–asset valuation and capital theory. Yet, they are not widely employed in policy assessment. First, they contravene the conceptual foundations of discounting in projects in which a social discount rate needs to be applied, as they do not correct for the higher opportunity cost of displaced investment (Burgess and Zerbe 2011). Second, they potentially introduce error in projects involving diverse capital assets and vintages, by assuming that a common depreciation rate exists for all alternative investments. Last, they require strong assumptions to be made to establish a representative depreciation rate.

The terms R_i and K_i are the two control variables that dictate the diffusion rate for each mitigation option. R_i denotes the instantaneous rate of diffusion, while K_i represents the ceiling of diffusion. Policy may target either or both of these elements of the diffusion process (see Section 3). The ceiling variable K_i will often be limited to being beneath some critical threshold $\bar{K}_i$, which denotes the population of potential adopters.

The logistic function is the classical form of $a_i\,(R_i, K_i, D_i)$ and has been used to describe S-shaped diffusion curves for a broad range of technologies (Rogers 2003). This equation is logistic with respect to the variable D_i and is typically defined through: a_i $(R_i, K_i, D_i) = R_iD_i(1{-}D_i/K_i)$. The shape of this function changes as the instantaneous rate of diffusion (R_i) and the ceiling (K_i) is altered. The term $K/2$ is the *inflection point* of the logistic function, the point where the derivative of a_i (R_i, K_i, D_i) with respect to the level of adoption $[D_i(t)]$ changes from positive to negative. Hence, $a_D > 0$ for $D < (K/2)$, $a_D = 0$ for $D = (K/2)$, and $a_D < 0$ for $D > (K/2)$. The form of the logistic equation specified above also implies the following derivative directions for a_i (R_i, K_i, D_i): $a_{D_iD_i} < 0$, $a_{R_i} > 0$, $a_{R_iR_i} = 0$, $a_{K_i} > 0$, $a_{K_iK_i} < 0$, and $a_{R_iK_i} = a_{K_iR_i} > 0$.

Improvements in environmental quality are a function of the level of adoption of all conservation practices. This is described through the benefit function, $b\left(\sum_{i=1}^{I} D_i(t)\right)$. It is assumed that these benefits can be expressed in monetary terms and consistent with theory, $b_{D_i} > 0$ and $b_{D_iD_i} < 0$.

The aggregate cost of diffusion is defined through the relationship c_i (R_i, K_i, D_i) and consistent with general theory, $c_{R_i} > 0$, $c_{K_i} > 0$, and $c_{D_i} > 0$. Higher values of R and K promote the pace, and hence the cost, of diffusion. Marginal diffusion costs increase with the level of adoption, as more widespread use of a mitigation option requires its uptake by progressively less-suitable users (Feder and Umali 1993; Rogers 2003).

Environmental quality in the terminal period incurs a cost to society in perpetuity. This is represented through the salvage-value function, $s\left(\sum_{i=1}^{I} D_i(T)\right)$ and consistent with general economic theory, $s_{D_i} > 0$ and $s_{D_iD_i} < 0$.

Returns across time are discounted to the current period using the social discount rate δ.

The objective function is defined in terms of total societal value J. The objective is to:

$$\max_{R_i, K_i} J = \int_{t=0}^{T} e^{-\delta t}\left[b\left(\sum_{i=1}^{I} D_i(t)\right) - \sum_{i=1}^{I} c_i(R_i, K_i, D_i(t))\right]dt + e^{-\delta T} s\left(\sum_{i=1}^{I} D_i(T)\right), \quad (2)$$

subject to Equation (1), $D_i(0) = D_i^0$ (where $D_i^0 > 0$), and $D_i(T) > 0$. The control problem consists of i state variables, $2i$ control variables and a fixed time horizon.

The problem may be solved using the standard maximum principle of optimal-control theory (Kamien and Schwartz 1991). This requires the formulation of the Hamiltonian function:

$$H = e^{-\delta t}\left[b\left(\sum_{i=1}^{I} D_i\right) - \sum_{i=1}^{I} c_i(R_i, K_i, D_i)\right] + \sum_{i=1}^{I} \lambda_i(t)[a_i(R_i, K_i, D_i) - l_i(D_i) - m_i(D_i)], \quad (3)$$

where the i state equations (Eqn 1) are appended to the objective function using the costate variables, $\lambda_i(t)$. The necessary conditions required for an optimal solution (Kamien and Schwartz 1991) are presented in Appendix S1. An explanation of key results follows.

The costate variable $\lambda_i(t)$ measures the change in social welfare associated with the marginal change in the level of adoption of mitigation option i. It is defined through:

$$\lambda_i(t) = e^{-\delta t}\int_{t}^{T} e^{(a_{D_i}-\delta-l_{D_i}-m_{D_i})(h-t)}(b_{D_i} - c_{D_i})dh + e^{(a_{D_i}-\delta-l_{D_i}-m_{D_i})(h-t)} s_{D_i(T)} \text{ for all } i. \quad (4)$$

Equation (4) highlights that diffusion improves environmental quality, but also increases costs. Both benefits and costs are eroded by the discount rate (δ), the rate of disadoption (l_{D_i}) and the rate of depreciation (m_{D_i}). The marginal value of diffusion ($\lambda_i(t)$) is compounded/discounted if the level of adoption is less/more than half of the inflection point. (This occurs through the a_{D_i} term in Eqn 4.)

The optimal instantaneous rate of adoption and ceiling level depends on the rule:

$$\frac{a_{R_i}}{a_{K_i}} = \frac{c_{R_i}}{c_{K_i}} \text{ for all } i. \quad (5)$$

It states that optimality requires balancing the benefit (left-hand side of Eqn 5) and cost (right-hand side of Eqn 5) of the two determinants of diffusion (R_i and K_i). This equation resembles the standard profit-maximising condition for a firm that employs two inputs (Varian 1992).

The optimal investment rule for diffusion is, for all i:

Part A Part B Part C

$$\delta = a_{R_i}(b_{D_i} - c_{D_i})/c_{R_i} + a_{D_i} - l_{D_i} - m_{D_i} = a_{K_i}(b_{D_i} - c_{D_i})/c_{K_i} + a_{D_i} - l_{D_i} - m_{D_i} \quad (6)$$

This equation has three parts. The discount rate in Part A is the return to capital available elsewhere in the economy. In comparison, Parts B and C define the rate of return received for changing the diffusion rate through the levers R_i and K_i, respectively. The first terms in Part B and Part C are similar. In Part B, the term is $a_{R_i}(b_{D_i} - c_{D_i})/c_{R_i}$, while in Part C, it is $a_{K_i}(b_{D_i} - c_{D_i})/c_{K_i}$. Each represents a benefit–cost ratio associated with a marginal change in the respective control variable (R_i in Part B and K_i in Part C). Each term contains several expressions (for $\mu = \{R_i, K_i\}$): (i) The a_μ term represents how much changing the respective control variable impacts the diffusion rate; (ii) The $(b_{D_i} - c_{D_i})$ term is the net benefit accruing to a marginal change in diffusion; (iii) The $a_\mu(b_{D_i} - c_{D_i})$ term in the numerator is the net benefit associated with changing the respective control variable; and (iv) The c_μ term in the denominator denotes the marginal cost of changing the respective control variable.

The benefit–cost ratio is augmented in Eqn 6 through a marginal stock effect (a_{D_i}). This measures how cumulative adoption affects the marginal value of diffusion. It stimulates/dampens marginal returns to adoption at levels of cumulative adoption below/above $\frac{K}{2}$. The marginal value of diffusion is further eroded by disadoption (l_{D_i}) and depreciation (m_{D_i}).

Equation (6) highlights the need to invest in the diffusion of each innovation to the point that its marginal contribution to social welfare equals the social discount rate. Factors that increase the centre or RHS terms in this equation increase the value of investing in diffusion. This can occur through: (a) improving the degree to which diffusion impacts environmental outcomes (b_{D_i}); (b) decreasing the overall degree to which diffusion level impacts its cost (c_{D_i}); (c) decreasing the degree to which a change in the determinant of diffusion (R_i or K_i) impacts cost (c_{R_i} and c_{K_i}); and (d) decreasing rates of disadoption through improving how innovations fit their users (l_{D_i}) and (e) decreasing rates of depreciation in mitigation capital (m_{D_i}).

Distortions from the optimal level of diffusion are expected, in practice. First, the private discount rate will likely be higher than the social discount rate (Brealey *et al.* 1997; Arrow *et al.* 2014), reducing incentives for environmental improvement. Second, the private landholder does not realise the benefits of reduced environmental damage; this dynamic externality reduces their incentive to reduce pollution load. Last, imperfect capital markets also reduce the inherent motivation to safeguard resource quality. An example is where land values do not reflect soil depth, thereby reducing incentives to conserve soil below the socially optimal level (McConnell 1983). These factors highlight a key need to utilise policy to address diffusion rates (R) and ceiling levels of adoption (K).

3. Policy framework

The model discussed in Section 2 characterises optimal diffusion pathways for different mitigation options. The mismatch between the net benefits of mitigation adoption for private and public agents motivates a need to identify suitable policies to achieve rates of adoption that align with attaining societal goals. Policy instruments impact the rate of adoption (*R*) and ceiling of adoption (*K*) in different ways. Levers that increase *R* typically improve awareness of the benefits of a mitigation option, rather than changing its relative advantage. In contrast, levers that increase *K* improve the relative advantage of the mitigation option to more landholders.

The impact of different policy instruments on adoption depends on the level of *involvement* present in the adoption decision (Boland *et al*. 2006; Kaine and Bewsell 2008): the personal investment – in terms of time, money and other resources – that private agents allocate to making that decision (Assael 1998). A fast, routine decision is typically considered as having a low level of involvement, while one that requires much time and deliberation has a high level of involvement. Low-involvement purchases commonly involve inexpensive products that are routinely purchased and the purchaser, the farmer, is unlikely to devote much time to the consideration of alternatives before purchase. An example is buying a new type of fertiliser (Hill *et al*. 2009). The product is purchased, trialled and evaluated. The product is purchased again if it compares favourably with regard to previous products, abandoned if not. In these circumstances, the purchase decision can be influenced by promotional activities at the point of sale.

By contrast, high-involvement purchases are generally much more important to the purchaser and intermittent in frequency; often, these options are expensive and involve some risk. Examples are the afforestation of pastoral area, changing livestock-breeding practices or purchasing land. High-involvement purchases evoke complex decision-making. This involves a systematic and iterative discovery process in which the purchaser learns about the attributes of products and develops a set of purchase criteria for choosing the most suitable option (O'Cass 2000; Pannell *et al*. 2006). With respect to farming, purchase criteria are based on the formulation of extensive chains of causal reasoning (Pennington and Hastie 1993) about the circumstances in which the product will offer a relative advantage (Pannell *et al*. 2006). Hence, the purchase criteria depend intimately on farm context: the farm system; its biophysical, economic and technological resources; and the needs of the farmer as the manager of a business.

Policy instruments to influence diffusion pathways may be broadly divided between regulation, incentives and extension (Pannell 2008). Here, incentives are interpreted as positive incentives. (Negative incentives work in a similar fashion, though their impact is opposite in direction.) At a broad level, incentives include subsidies, conservation auctions/tenders, taxes and tradable-permit systems (Pannell 2008). Table 1 provides a summary of the potential for these different policy mechanisms to impact the rate (*R*) or ceiling (*K*) of diffusion. These classifications are provided for three forms of mitigation option. These options differ by the level of involvement invested in the adoption decision and the complexity of the innovation. Complexity is broadly interpreted as whether a mitigation option is an incremental (low complexity) or radical (high complexity) innovation in a given farm context. See Henderson and Clarke (1990) for a precise definition of complexity and Kaine *et al*. (2008) for applications to agriculture. The adoption of radical or complex innovations necessarily requires a substantial investment of time and effort in gathering information, considering options, evaluating potential outcomes and planning implementation. This will necessarily invoke high-involvement decision-making. Hence, the case of a low-involvement, complex mitigation option appears highly unlikely and so is not considered below.

3.1 High involvement, complex mitigation options

The first mitigation option type in Table 1 concerns high-involvement decisions about a complex practice. An example is the consideration of whether to house dairy cattle to reduce soil compaction and capture their urine before deposition on pasture to reduce nitrogen leaching. The potential for regulation to influence diffusion is high for this type of mitigation option. By making adoption compulsory, farmers are forced to adopt the mitigation option even though it may not offer a relative advantage to them. This infers they will incur the substantial costs that are associated with implementing such a complex change. Hence, regulation can modify both R and K. The potential for incentives to influence the rate of diffusion is low, unless they are set high enough to offset most, if not all, of the costs of change. In other words, the incentive itself becomes a purchase criterion. The potential for extension to influence the ceiling level of diffusion is limited, as extension does not alter the farm contexts that determine the suitability of a certain mitigation option, that is, its relative advantage. Still, extension can increase the rate of diffusion, primarily by

Table 1 Potential impacts of regulation, incentives and extension on the diffusion ceiling (K_i) and diffusion rate (R_i), for different types of mitigation option. The case of low-involvement, complex mitigation options is omitted, as typically radical innovations will require high-involvement decision-making

Conditions		Potential for regulation to influence practice change		Potential for incentives to influence practice change		Potential for extension to influence practice change	
Involvement	Complexity	Ceiling (K_i)	Rate (R_i)	Ceiling (K_i)	Rate (R_i)	Ceiling (K_i)	Rate (R_i)
High	High	High	High	Low†	Low‡	Low	High
High	Low	High	High	Low†	High	Low	Low
Low	Low	High	Low	Low†	High	Low	Low

Note: †If the incentive offsets most or all of the cost of change. ‡Depends on whether the practice offers a relative advantage and, if not, the fraction of the cost of change that the incentive offsets.

reducing search and learning costs that are typically higher for a complex practice.

3.2 High involvement, simple mitigation options

The second mitigation option type in Table 1 concerns high-involvement decisions about a simple practice. An example is fencing streams to reduce streambank erosion, where the simplicity of adopting stream fencing will vary depending on the farm context (Kaine and Wright 2017). Again, the potential for regulation to influence the extent of change is high. Landholders will most likely be aware of the necessity for change because of their high involvement. Since search and learning costs are low for a simple practice, the motivation to delay changing practice will be weak (assuming any loss in relative advantage is small). The potential for incentives and extension to influence the ceiling of diffusion is low, given these actions do not change the farm systems to which the mitigation option is suited, and therefore the purchase criteria employed by farmers to assess relative advantage. However, the potential for incentives to influence the rate of change is high because even a relatively small incentive can trigger trialling of the practice, or offset a substantial proportion of the costs of change. In contrast, the potential for extension to influence the rate of change is low, primarily because search and learning costs are small because it is a simple practice.

3.3 Low involvement, simple mitigation options

The third mitigation option type in Table 1 concerns low-involvement decisions about a simple practice. An example is reducing fertiliser application rates to decrease nutrient loss. For this type of mitigation option, the ceiling on diffusion is defined by the size of the market for those products for which the innovation is a substitute. This is not easily altered through incentives or extension. The potential for regulation to influence the rate of change is likely to be low because landholders' awareness of the need to change will be limited, given their low involvement with the mitigation option. The potential for incentives to influence the rate of change in these circumstances is high because even a relatively small incentive can trigger trialling of the practice or offset a substantial proportion of the costs of change. The potential for extension to influence the rate of change is low, primarily because landholders do not need to devote time and effort to learning about the practice because it invokes low-involvement decision-making.

4. Application

The focus of the case study is to demonstrate the application of the framework. Numerical models can range from the simple to the complex.

This case study incorporates a substantial level of detail. Simpler applications are easier to understand. However, more detailed applications provide insights into mechanism design and a framework's usefulness for pragmatic policy assessment.

The empirical model is used to identify optimal diffusion for different mitigation options in Section 4.3. The policy framework from Section 3 is then used to identify specific policy actions that can help to achieve these ends. This process is described in Section 4.4.

4.1 Case study

The pastoral sector in New Zealand (NZ) is a primary source of regional and national income, producing 40 per cent of merchandise exports by value in 2017 (SNZ, 2018). However, there is strong societal concern regarding the impacts of land use on water quality, with soil erosion from pastoral farms a major issue (MFE, 2017). NZ makes up only 0.2 per cent of global land area, but produces around 2 per cent of global sediment loss due to extensive land clearance, high rainfall, a prevalence of steep slopes, and fragile lithologies (Syvitski *et al.* 2005). Sediment loss is problematic since it can decrease agricultural productivity, while its delivery to water can impair recreational values, encourage eutrophication and smother ecological communities, both in freshwater and marine environments.

The Waipa River provides around 70 per cent of the total sediment load in NZ's largest waterway, the Waikato River (Hill 2011). The Waipa River at the town of Whatawhata is a major recreational site, especially for swimming and kayaking, close to the large urban centre of Hamilton (pop. approximately 160,000). Water clarity at this site has been around 0.6 m for the last 30 years. Recent research highlights that community aspirations are for this site to have clarity above 1 m, with high nonmarket values being estimated for improvements in this attribute of water quality (Phillips 2014).

The catchment is around 280 km^2 in size, with around 75 per cent of this area consisting of pastoral agriculture. Pastoral land is split evenly between dairy and sheep farming, though the highest erosion rates are experienced on the latter farms given their general location on steeper slopes. Total erosion rates average around 730 t/km^2 per year, with most of this split across streambank and hillslope erosion on pastoral-based dairy and sheep farms. This high rate reflects the steep slopes, high rainfall and weak lithology characteristic of the region. Streambanks and hillslopes on dairy land are responsible for 12 and 17 per cent of total erosion, respectively. In comparison, streambanks and hillslopes on sheep land are responsible for 25 and 38 per cent of total erosion, respectively. The residual 8 per cent of total erosion is allocated to miscellaneous land uses, including forest and urban areas.

Several key management options are available for soil conservation in this region: (i) Stream fencing: Streambanks are fenced so that livestock cannot promote soil loss from stream margins. This strategy generally achieves a moderate reduction in streambank erosion. It is highly adoptable on dairy farms, due to its lower cost on dairy farms that are generally flatter; (ii) Farm planning: Environmental managers work with farmers to help them identify and implement strategies to reduce soil loss. Key strategies within this approach are partial and full afforestation of different parts of each farm. This strategy generally achieves a moderate reduction in hillslope erosion; and (iii) Sediment bunds: Earth dams are created at key points in valleys to capture sediment suspended in small streams. This strategy generally achieves a significant reduction in sediment loss, from both hillslope and streambank sources.

These management options are defined individually for dairy and sheep farms in the empirical application.

4.2 Empirical application

The model outlined in Section 2 is applied to identify key management implications for the case study outlined above. A full description of the numerical model is provided in Appendix S2. Data for the model are drawn from multiple sources.

A 30-year time horizon is used for the empirical model. Uncertainty precludes the use of a longer horizon. Additionally, discounting decreases the value of studying a longer time horizon, particularly given the standard discount rate recommended by the NZ government (δ = 0.07) (Appendix S2).

The link between nonmarket benefits and mean clarity observed at the recreational site is drawn from Phillips (2014). Benefit functions for both users and nonusers are estimated from data identified using choice modelling. These numbers are weighted in the analysis according to use data. The characteristics of different land parcels, current and maximum levels of adoption, and cost and efficacy levels for mitigation options are taken from Doole (2016).

Costs generally increase with greater diffusion, as mitigation options start to be used on farms to which they are less suited (Feder and Umali 1993). This information is difficult to identify in practice. A scarcity of appropriate data in the study region motivates the use of an informal estimation procedure. A triangular distribution is defined by three parameters: the minimum; average; and maximum values of the distribution. Triangular distributions for per unit costs are generated for each mitigation. These are based on extensive literature review and expert opinion (Doole 2016). Intermediate values between each point are then estimated through linear interpolation. Finally, the linear regression model defining per unit costs is fitted to these values. The triangular distributions representing costs for farm planning and sediment bunds are symmetric, given a lack of other data. In contrast, the distribution of per unit cost for stream fencing – defined in units of \$/km – is asymmetric, with average cost corresponding to a 30 per cent adoption rate. This assumption is drawn from a review of fencing costs, with lower values more likely given broad flexibility available in fence design and construction (Grinter and White, 2016). The implications of holding the per unit mitigation cost fixed at its average are explored in Section 4.3. This sensitivity analysis is important, given the dearth of data relating to how per unit cost changes with diffusion.

Soil loss levels for different parcels of land in the catchment are estimated using the New Zealand Empirical Erosion Model (NZEEM) (Dymond *et al.* 2010). NZEEM estimates the erosion rate present on a given piece of land as determined by rainfall, rock type, slope and vegetation cover.

The model relating the link between total soil load and clarity is drawn from Yalden and Elliott (2015). This model computes beam attenuation at the recreational site as a function of suspended sediment load and yellow-substance incidence (arising from natural tannins present in some soil types, e.g. peat).

The base case of the model involves a 7 per cent discount rate, 60 per cent of total sediment loss coming from streambanks, dairy fencing costing \$4,000 km^{-1} and per unit mitigation costs increasing with total diffusion. The model runs include experiments involving:

1. Definition of discount rates of 2, 7 and 12 per cent;
2. Allowing per unit mitigation cost to remain fixed as the total level of diffusion increases;
3. Simulation of decreases in the diffusion rate; and
4. Comparison of output to results from a static model.

Item #3 outlines simulating decreases in the diffusion rate. These chiefly arise due to disadoption and depreciation (see Eqn 1). Mitigation options are costed at a level consistent with a lifespan of at least 30 years. Nonetheless, the impacts of decreases in diffusion provide rich insight. A simple formulation is used to explore this. Disadoption and depreciation are combined to form one measure of loss (L) that moderates the diffusion rate. The impacts of four loss rates are explored as follows: 2.5; 5; 7.5; and 10 per cent of the current level of diffusion ($D_{\mathrm{i}}(\mathrm{t})$). In these cases, it is assumed that there is no salvage value of capital.

The terms R_i and K_i are determined endogenously through optimisation. These variables yield an optimal diffusion rate for each mitigation, given values for disadoption and depreciation.

Lower and upper bounds are set on R_i and K_i.

The ADOPT tool (Kuehne *et al.* 2013) is used to estimate the minimum rate of adoption for each mitigation option; this is used alongside historical information to determine the natural path of diffusion that would occur without policy intervention. This software identifies the diffusion curve that best fits a certain mitigation option, based on answers to a set of predefined questions that together help to determine how rapidly adoption is expected to occur. The optimal instantaneous diffusion rate – as determined through R_i – must be greater than or equal to this natural rate in the model. This is appropriate given the focus on mitigation capital; that is, a technology or practice that has defined off-site impacts in a context where environmental improvement is warranted. In some cases, it may be optimal to retard the diffusion of a given technology or practice, for example, where its uptake has negative off-site impacts.

The maximum level of diffusion is determined through identifying the maximum physical extent to which each mitigation option can be adopted across the watershed and the existing level of adoption. The optimal ceiling to diffusion – as determined through the control variable K_i – must be less than or equal to this quantity.

The continuous-time model is solved with nonlinear programming using direct-control transcription (Betts 2009). This involves discretisation of the continuous-time horizon and integration of the differential equations across the discrete mesh using a numerical integration procedure. State and control constraints are imposed at each discrete point. The model is solved using the MSNLP solver in GAMS (Ugray *et al.* 2009). MSNLP solves a nonlinear-programming problem from a high number of alternative starting points, consequently refining the set across time to converge towards the single-best (i.e. global) solution.

4.3 Results

Figure 1 outlines the diffusion paths for the optimal set of mitigation options for the base case – consistent with a discount rate of 7 per cent. The first half of the time horizon is dominated by the rapid adoption of stream fencing on dairy farms. Farm plans on sheep farms are adopted slowly and do not reach a high level of adoption, whereas sediment bunds are used on around 40 per cent of sheep farms after their adoption starts to gain momentum in the second half of the time horizon.

Figure 2a outlines the optimal diffusion paths that exist at a discount rate of 2 per cent. The rapid, high adoption of stream fencing on dairy farms is equivalent to that seen at a discount rate of 7 per cent. However, in contrast to the base case (Figure 1), the rate of farm plan and sediment-bund adoption on sheep farms is much higher. On sheep farms, farm plans are implemented by all potential adopters after around 25 years, while sediment bunds are used by nearly all potential adopters after 30 years. Figure 2b sets out optimal mitigation use with a discount rate of 12 per cent. There is only one mitigation option used in this case: dairy stream fencing. It is adopted rather rapidly, but is only ever used by 75 per cent of the target population after diffusion ceases.

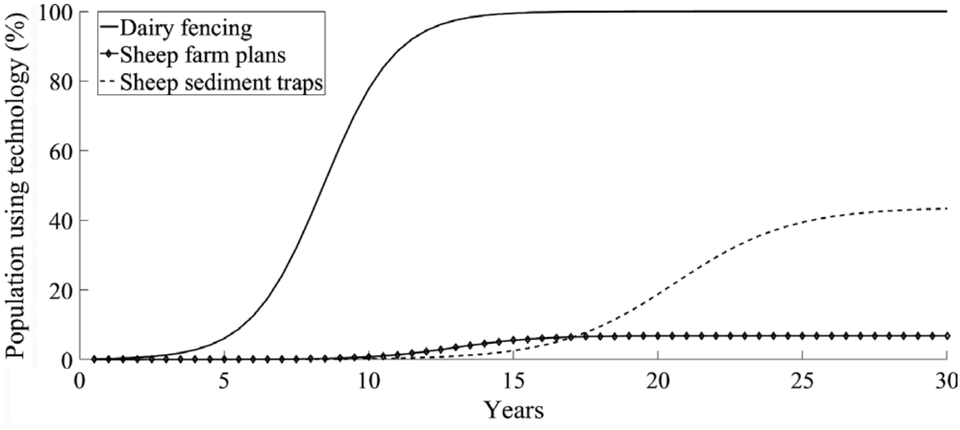

Figure 1 Optimal diffusion of different mitigation options under the set of base assumptions. The discount rate is 7%.

Figure 3a outlines the time paths for water clarity under the distinct diffusion paths shown in Figures 1 and 2. Water clarity exhibits only minor improvement at the high discount rate (12 per cent), but improves by 22 per cent, relative to the current level, at the baseline discount rate of 7 per cent. Water clarity improves greatly, to around 1 m, at the low discount rate (2 per cent). All time paths for clarity are characterised by a slow evolution towards their terminal state. Figure 3b sets out the reductions in sediment load that occur across the catchment to achieve these clarity outcomes. Reductions of 39, 17 and 5 per cent are achieved by the end of the time horizon for discount rates of 2, 7 and 12 per cent, respectively.

The standard assumption in the base model is that the marginal cost of a given mitigation increases with the level of adoption. This is justified because as the level of adoption increases, abatement practices will start to be used by producers for whom they are less appropriate. For example, this may be to do with how a mitigation option is more expensive to apply on one farm, relative to another, because of biophysical factors (e.g. rainfall, slope, soil type) or farmer management ability. An alternative assumption is that the marginal cost of a given mitigation does not change with the level of adoption. This implies a greater homogeneity among farms, in terms of the economic value of a given mitigation option. Figure 4 displays the impacts of this alternative assumption, involving a constant marginal cost for all mitigation options. In the base case, farm plans and sediment bunds are used at most by around 5 and 40 per cent of potential users, respectively. However, if per unit costs remain constant at their mean, optimal diffusion involves the full adoption of these mitigation options across the planning horizon, together with the fencing of dairy streams (Figure 4).

The static version of the model is also solved. This is done through defining the model in a single-period, equilibrium format (Doole 2015). This solution

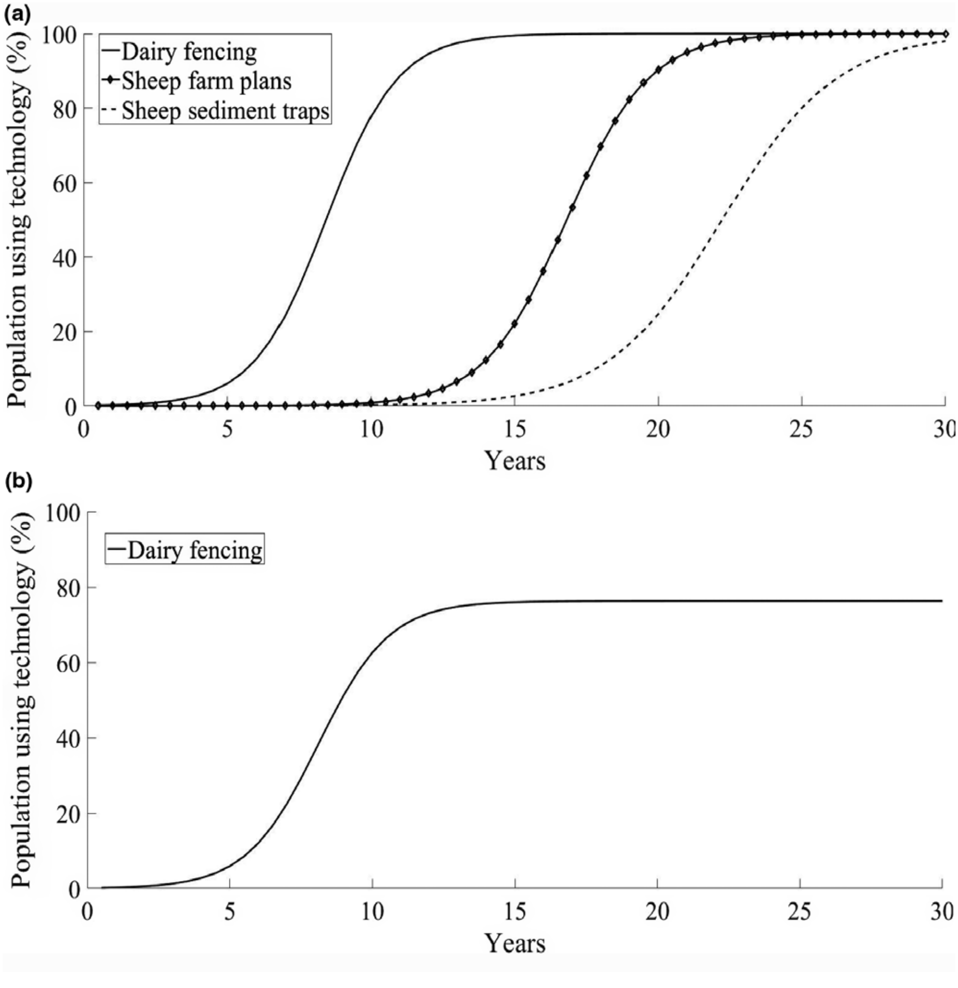

Figure 2 The impact of alternative discount rates on the optimal diffusion of different mitigation options. Discount rates utilised in the generation of these graphs are: (a) 2%; and (b) 12%.

is important to explore the significance of considering the dynamic aspects of resource management within the model. The optimal results prescribe no mitigation (data not shown), with clarity remaining at its base level (0.6 m). This outcome remains with the removal of increasing marginal per unit mitigation costs.

Table 2 presents the base and optimal levels of the control variables in the empirical model. Interpretation requires a consideration of both ceiling and rate variables, for each mitigation option. Dairy farm plans, dairy bunds and sheep stream fencing play minor roles (Table 2). This is shown in Table 2 in that the optimal rates of diffusion do not change, while the optimal ceilings either stay the same or decrease to their lower bound (0.001). In contrast, attractive practices are dairy stream fencing, sheep farm plans and sediment

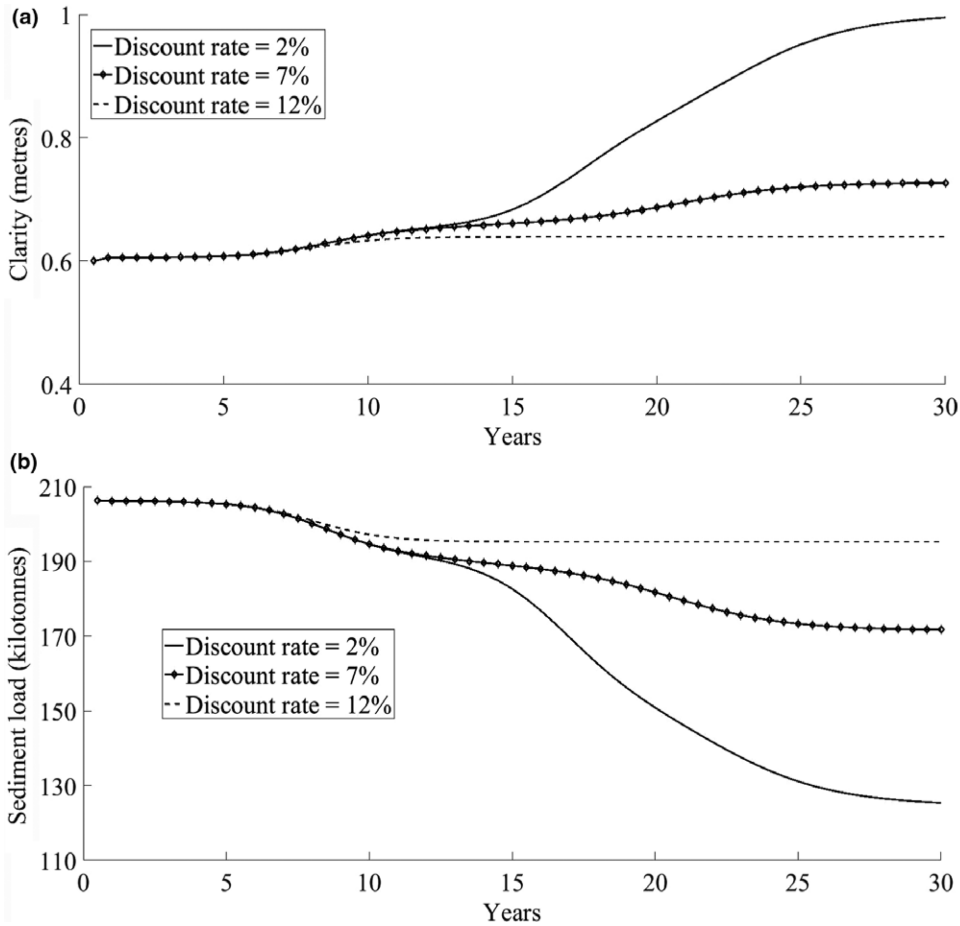

Figure 3 The impact of alternative discount rates on: (a) water clarity; and (b) total sediment load in the catchment.

bunds on sheep farms. In Table 2, these are indicated by substantial increases (400 per cent or more) in the optimal rate of diffusion. The ceilings are also set at their base level for dairy stream fencing. However, they decrease for sheep farm plans and bunds, as the optimal diffusion pathway for these options involves a faster trajectory towards a lower cap.

Table 3 reports how the optimal levels of the ceiling and rate variables change for different levels of diffusion loss (L). These levels of diffusion loss represent decreases in the diffusion rate due to disadoption and depreciation (Section 4.2). Several results are noteworthy. First, the optimal level of net benefits declines with higher loss rates (data not shown). For example, the present value of net benefits at the catchment level is \$2.32 m, \$1.63 m and \$1.25 m for loss rates of 0, 5 and 10 per cent, respectively. Second, less environmental improvement occurs under optimal management when disadoption and depreciation occur. For example, clarity in the terminal period

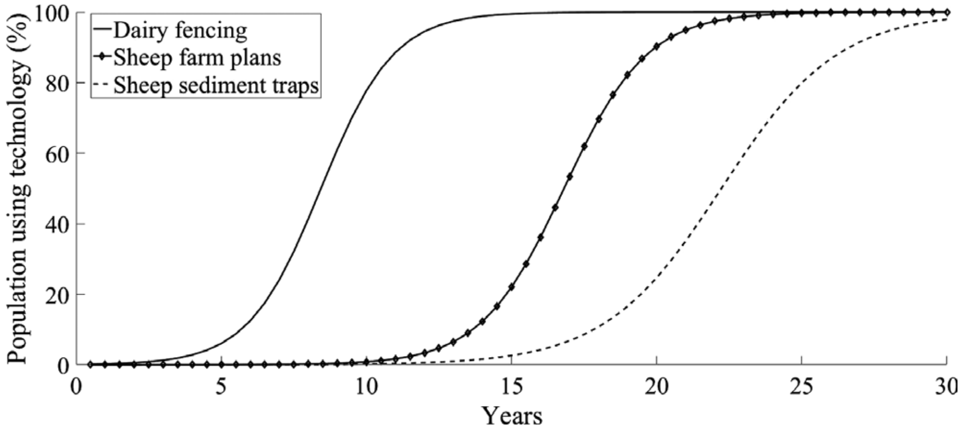

Figure 4 Optimal diffusion of different mitigation options with constant per unit mitigation costs.

Table 2 Baseline and optimal levels of the diffusion ceiling (K_i) and diffusion rate (R_i) for the base model. The discount rate is 7%

Mitigation	Ceiling (K_i)		Rate (R_i)	
	Base	Optimal	Base	Optimal
Dairy stream fencing	0.35	0.350	0.20	0.80
Dairy farm plans	0.90	0.900	0.10	0.10
Dairy bunds	0.90	0.001	0.15	0.15
Sheep stream fencing	0.55	0.001	0.05	0.05
Sheep farm plans	0.90	0.060	0.10	0.70
Sheep bunds	0.90	0.400	0.10	0.50

is 0.73, 0.67 and 0.64 m for loss rates of 0, 5 and 10 per cent, respectively (data not shown). Third, a strong focus on stream fencing on dairy farms is maintained, though the optimal ceiling rate does fall away slightly with higher levels of diffusion loss (Table 3). Fourth, farm planning on sheep farms is not utilised once positive loss rates are assumed. This reflects the high cost of this activity and its borderline level of value in the base case ($L = 0$). Last, optimal levels of diffusion fall gradually with the simulated level of loss, for sediment bunds on sheep farms.

Disadoption and depreciation erode the environmental benefits associated with a high capital outlay borne by the agricultural sector. Meaningful reductions in diffusion are observed for realistic loss rates of 2.5 and 5 per cent, highlighting the sensitivity of model output to this parameter. Stream fencing on dairy farms remains largely unaffected. Yet, farm planning on sheep farms is no longer used and the ceiling for sediment bunds on sheep farms falls by three quarters. This would have important implications for policy formulation. These results demonstrate the importance of considering disadoption and depreciation in studies of this kind.

Table 3 Levels of the diffusion ceiling (K_i) and diffusion rate (K_i) for the base model and for optimisation with the loss rate (L) representing decreases in diffusion due to disadoption and depreciation set at 0%, 2.5%, 5%, 7.5% and 10%. A loss rate of 0% (i.e. L = 0) corresponds to the optimal solution shown in Table 2

	Ceiling (K_i)						Rate (R_i)					
	Base	L = 0	L = 2.5%	L = 5%	L = 7.5%	L = 10%	Base	L = 0	L = 2.5%	L = 5%	L = 7.5%	L = 10%
Dairy, stream fencing	0.35	0.350	0.350	0.350	0.310	0.260	0.20	0.80	0.80	0.80	0.80	0.80
Dairy, farm plans	0.90	0.900	0.900	0.900	0.900	0.900	0.10	0.10	0.10	0.10	0.10	0.10
Dairy, bunds	0.90	0.001	0.001	0.001	0.001	0.001	0.15	0.15	0.15	0.15	0.15	0.15
Sheep, stream fencing	0.55	0.001	0.001	0.001	0.001	0.001	0.05	0.05	0.05	0.05	0.05	0.05
Sheep, farm plans	0.90	0.060	0.001	0.001	0.001	0.001	0.10	0.70	0.10	0.10	0.10	0.10
Sheep, bunds	0.90	0.400	0.230	0.110	0.020	0.001	0.10	0.50	0.50	0.50	0.50	0.10

4.4 Policy implications

The limitations of the unfavourable mitigation options in Table 2 are intuitive. Dairy farm plans are expensive and have little capacity to influence soil erosion, given the flatter topography of most dairy farms. Sediment bunds on dairy farms are also limited in their efficacy, as sediment loss from their catchment area is much lower than on sheep farms. Stream fencing is expensive on sheep farms due to their steeper, more incised terrain.

Stream fencing on dairy farms is cost-effective, simple, and requires low-involvement decision-making. Indeed, larger streams have already been fenced on many farms, given the benefits of stock exclusion for animal health (e.g. to prevent ingestion of liver fluke) and to reduce livestock mortality from misadventure. It is optimal to improve the diffusion rate well above its baseline level (Table 2). The policy framework from Section 3 highlights that incentives would be very suited to increasing the adoption rate. The potential for incentives to influence diffusion is significant, since it can stimulate trialling or offset the costs associated with the uptake of high involvement, simple mitigation options (Section 3). The model itself can be used to determine what incentive level would be required to achieve the requisite rate of adoption.

Farm plans are valuable to reduce sediment loss from hillslope erosion from sheep farms. However, they are expensive to undertake. They are complex strategies since they involve the implementation of an integrated approach to reducing sediment loss from the farm. They also evoke high-involvement decisions since the on-site benefits are not easily apparent. Table 2 shows how the optimal ceiling is well below the full population of potential adopters. This highlights that the model could be used to identify where the farm plans are best located across the catchment. The policy framework in Section 3 highlights how regulation and/or extension could be used to accelerate diffusion rates. The latter is particularly attractive, as it represents a cost-effective means to reduce search and learning costs.

Sediment bunds on sheep farms are expensive, but are effective in reducing the sediment lost downstream from both hillslope erosion and streambank erosion. They are simple strategies to fit within a farm system, but evoke high-involvement decisions since they yield little on-site benefit. The policy framework from Section 3 highlights that regulation and/or incentives are both valuable options for improving diffusion rates. The model can be used to determine the best ways to achieve this. Further, it can help identify where bunds are located to achieve maximum impact.

5. Discussion

The inherently dynamic nature of environmental degradation has been recognised in applied economics since the pioneering work of Bunce

(1942). However, the application of dynamic models is still the exception, rather than the rule, in applied work. This is typically because of a scarcity of data, expertise and time. Additionally, the development of large models can complicate accessibility, the identification of trends and reporting. The results of the dynamic analysis in Section 4 show that mitigation is valuable and ideally should follow a nuanced pathway, given that the value proposition associated with investment in alternative forms of mitigation capital changes across time under optimal management. In contrast, a static version of the model reports that there is no value in performing mitigation; the costs of action outweigh the benefits. Accordingly, this study reinforces that dynamic analysis offers a richer lens through which to analyse environmental management. Central to this argument are the capacity to study diffusion processes (Pannell *et al.* 2014) and the key role that durable mitigation capital plays in addressing human activity with dynamic externalities (Grepperud 1997). Conceptually, durable capital provides a stable source of environmental mitigation, particularly when it does not depreciate quickly and/or cannot be readily disadopted. This contrasts with activities that are less stable in light of climate and market variation – such as reductions in livestock density or fertiliser application.

The empirical application emphasises the importance of the discount rate to investment in durable mitigation capital. At the baseline discount rate of 7 per cent, the fencing of streams on dairy farms occurs rapidly and to a high level, while sediment bunds on sheep farms are utilised later in the horizon (Figure 1). A low discount rate (2 per cent) reduces the opportunity cost of investing in environmental restoration. Thus, in this scenario, all streams on dairy farms are fenced, all sheep land is subject to farm planning, and sediment bunds are built at all potential sites on sheep farms (Figure 2a). In contrast, a high discount rate decreases the economic incentive for environmental conservation, as money is better spent on alternative investments. In this case, the only mitigation activity involves 80 per cent of dairy streams eventually being fenced (Figure 2b). These diffusion pathways translate into greater levels of sediment reduction, and hence greater improvements in water clarity, at lower discount rates (Figure 3). This relationship between the discount rate and stocks of environmental quality is well known, with greater investment in environmental resources being optimal at lower discount rates (Clark 2010). However, the novel finding here is that in the case of nonpoint pollution policy, the main driver for this environmental improvement is through an intermediate, mitigation capital effect. Alternative investment opportunities impact the rate of investment in abatement options, and this has subsequent impacts on the environment.

The dynamic view of environmental restoration offered by the framework demonstrates how divergent private and public discount rates can contribute to suboptimal levels of adoption for environmental mitigation option. An optimal investment rule for diffusion is derived in Equation (6). Optimal management requires that the environmental benefits and abatement costs associated with changes in the rate and ceiling of diffusion for each mitigation option should be balanced with the social discount rate. The private discount rate used by a farmer in the adoption decision is likely to be higher than the social discount rate (Brealey *et al.* 1997; Arrow *et al.* 2014). This adds an additional source of externalities, beyond the standard argument that landholders' economic incentives do not align with public goals. Thus, policy is a key lever to help transition towards rates of diffusion and maximum levels of adoption that are more consistent with socially optimal environmental improvement.

Basing policy assessment on a framework centred around diffusion principles allows the consideration of per unit costs for mitigation options that vary across a population. The case study highlights that costs that increase with adoption level can amend the optimal diffusion profiles. Optimal diffusion rates profoundly slow for more expensive mitigation options when costs increase with greater levels of adoption (cf. Figures 1, 4). Higher levels of diffusion are observed later in the horizon; yet, these empirical outcomes confirm that the effects of discounting are insufficient to dominate higher per unit costs. This highlights key research needs associated with how and why the costs of innovations change among different adopter categories.

The policy framework developed in this paper demonstrates that regulation is a means of influencing both the ceiling and rate of diffusion in high-involvement decisions. Incentives have minimal impact on the ceiling of diffusion, as they do not change the farm contexts that determine the attractiveness of a mitigation option to a landholder. An exception may occur where an incentive is sufficiently large to exceed the costs of adopting a practice, including offsetting the loss in relative advantage. For complex mitigation options, incentives can accelerate the rate of diffusion if they offset a substantial proportion of the cost of change. Incentives for simple mitigation options can accelerate change by promoting trialling. The only set of circumstances for which there is a high potential for extension to increase the rate of adoption is when landholders are highly involved with a complex change to farm practice. This alignment arises from the capacity for extension to reduce search and learning costs for a complex innovation and producers' willingness to engage in extension activities when they are highly involved.

The need to approach the management of nonpoint pollution through the implementation of multiple mitigation options has been recognised by both scientists (Durand *et al.* 2015; Hamilton *et al.* 2016) and economists (Balana *et al.* 2011; Tang *et al.* 2016). This study adds another insight to this literature showing it is important to consider how the temporal intensity of each mitigation action changes over time, both individually and in combination with other actions. The analytical model demonstrates that the dynamic pathway of diffusion for each mitigation option will likely differ from that for others. This arises from differences in the way that net benefits, disadoption and depreciation accrue over time to different mitigation options (Section 2). Further, the case study highlights how optimal management consists of one wave of diffusion for one mitigation option following another – regardless of the discount rate (Figures 1, 2). Model output shows that cheaper mitigation options that only treat part of the problem – such as the fencing of streams on dairy farms – can play an important role early in the implementation phase, followed by more expensive, but also more effective, abatement options (e.g. the use of sediment bunds in Figure 1). These findings demonstrate the importance of considering dynamics and diverse rates of diffusion among mitigation options, extending the insights offered by static models.

A focus on diffusion in policy evaluation allows the adoptability of different measures to be explicitly represented in the assessment. This extends the traditional paradigm within environmental economics that centres on cost and mitigation efficacy. It also highlights that environmental managers can exploit variation in the levels of resistance that polluters have towards certain abatement options. An example has been the industry-led efforts of the NZ dairy sector to fence larger streams to reduce nutrient and sediment loss from farms. This activity has been widely adopted, and the high rates of existing adoption are factored into the present analysis. Yet, this study suggests that the benefits of this action could have been augmented through better links with public funding and policy. Model output in the case study identifies how stream fencing on dairy farms should dominate mitigation action in the short term (Section 4.3). Likewise, the application of the policy framework (Section 3) to this case study highlights that incentives would be a very suitable tool to encourage greater diffusion (Section 4.4). This highlights how considering the adoptability of mitigation alternatives sharpens the discussion on how best society can gain leverage to work with polluters to reduce their environmental footprint. Further, embedding the diffusion ethos in a policy framework allows decision makers to focus more attention on the best means to manipulate diffusion rates. The diffusion lens highlights the need to consider the complexity and level of involvement that a landholder experiences with each mitigation option in policy design.

A focus on diffusion also has benefits for building greater social awareness of the pollution problem. It may take many years for observable shifts in environmental quality to occur. This is demonstrated in Figure 3. Also, lags extending from several decades to hundreds of years may exist for nitrogen moving through groundwater (Sanford and Pope 2013; Anastasiadis *et al.* 2014). Social awareness of diffusion levels can be a valuable benchmark in this situation, to display progress towards the ultimate goal of restoration.

Diffusion processes provide a natural and pragmatic framework with which to work with communities, especially farmers and industry. In practical terms, options that are highly adoptable are also valuable catalysts for mitigation momentum in a collective strategy to improve the environment.

Several examples exist in NZ already. The *Sustainable Dairying — Water Accord* has motivated 26,197 km of stream fencing and forming of 44,000 stock crossings (DairyNZ/DCANZ, 2016). Similarly, Taranaki Regional Council have implemented 2,587 riparian plans that have resulted in 12,200 km of stream fencing and 7,700 km of riparian vegetation (Bedford 2017). Exploiting these high leverage opportunities can help to build social ambition, momentum, motivation and will. Pathways to restoration can be long and difficult. Starting a policy journey with tasks that are more easily achieved helps to provide experience, focus and progress, providing a strong foundation for future steps.

The treatment of diffusion processes also allows the consideration of how the cost of durable mitigation capital varies across a population. The central thesis of diffusion is that mitigation options offer different advantages to different members of a population, depending on their individual biophysical, socio-economic and technical context. An important tenet is costs will typically increase with higher diffusion, as the mitigation option starts to be used in environments to which it is less suited (Feder and Umali 1993; Rogers 2003). This factor is included in the base case and dampens the diffusion of all options, except the fencing of streams on dairy land (Figure 1). However, when this relationship is removed, farm planning and the use of sediment bunds on sheep farms are widely adopted too (Figure 4). This demonstrates how the consideration of diverse marginal costs of mitigation across a population (a feature central to the analysis of diffusion rates and maximum levels of adoption) can have profound impacts on strategies to address environmental degradation.

An increased emphasis on diffusion also places greater focus on the need to design agricultural practices and systems that reduce contaminant loss and are cost-effective, but are also highly adoptable. This establishes the need to work closely with stakeholders, especially producers, throughout the process of technical innovation (Pannell *et al.* 2006). Moreover, it highlights the need to consider both the rate and ceiling of diffusion; environmental policy must act on both levers, recognising their interdependent effects on social benefits and costs. However, while technical innovation is part of this, some authors highlight the need for significant structural change if agriculture is to retain its social licence to produce (Bos *et al.* 2009). This typically involves the design of new farm systems; those that better meet the needs of society, including through reduced environmental impacts. These options allow the potential for the transformation of agricultural landscapes, but must also be considered through the lens of diffusion, given that low-cost structures within existing systems provide inertia to the retention of the *status quo*. Additionally, the diffusion of practices that consist of multiple options is often slow and limited, given their complexity and high information needs (Feder and Umali 1993). A policy implication is that society may benefit from the subsidisation of transformative agricultural systems until they are more competitive with existing approaches (Moreau 2004).

This research highlights the importance of focusing the design of policy journeys on the diffusion of mitigation options and a need to consider the relative adoptability of these options. At a practical level, it provides a natural framework for working with stakeholders to engender social support and momentum on a pathway towards sustainable agricultural production. In a world where current, exploitative practices are ingrained in low-cost production structures, the chance to stage gradual change and inform it through an accessible, pragmatic framework is highly attractive.

References

Anastasiadis, S., Kerr, S., Nauleau, M., Cox, T. and Rutherford, K. (2014). Does complex hydrology require complex water quality policy?, *Australian Journal of Agricultural and Resource Economics* 58, 130–145.

Arrow, K.J., Cropper, M.L., Gollier, C., Groom, B., Heal, G.M., Newell, R.G., Nordhaus, W.D., Pindyck, R.S., Pizer, W.A., Portney, P.R., Sterner, T., Tol, R.S.J. and Weitzman, M.L. (2014). Should governments use a declining discount rate in project analysis?, *Review of Environmental Economics and Policy* 8, 145–163.

Assael, H. (1998). *Consumer Behaviour and Marketing Action*. South Western College Publishing, Cincinnati.

Balana, B.B., Vinten, A. and Slee, B. (2011). A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: key issues, methods, and applications, *Ecological Economics* 70, 1,021–1,031.

Baum, A. (1991). *Property Investment Depreciation and Obsolescence*. Routledge, London.

Baum, A.E. and MacGregor, B.D. (1992). The initial yield revealed: explicit valuations and the future of property investment, *Journal of Property Valuation and Investment* 10, 709–726.

Bedford, G. (2017). *Transforming the Stream Banks of Taranaki, New Zealand: Voluntary Regional-Scale Stream Enhancement*. Taranaki Regional Council, New Plymouth.

Betts, J.T. (2009). *Practical Methods for Optimal Control Using Non-Linear Programming*. Siam, Philadelphia.

Boland, A., Bewsell, D. and Kaine, G. (2006). Adoption of sustainable irrigation management practices by stone and pome fruit growers in the Goulburn/Murray Valleys, Australia, *Irrigation Science* 24, 137–145.

Bos, B., Koerkamp, P.W.G., Gosselink, J.M.J. and Bokma, S. (2009). Reflexive interactive design and its application in a project on sustainable dairy husbandry systems, *Outlook of Agriculture* 38, 137–145.

Boucekkine, R., Fabbri, G. and Gozzi, F. (2010). Maintenance and investment: complements or substitutes?, *Journal of Economic Dynamics and Control* 34, 2,420–2,439.

Brealey, R.A., Cooper, I.A. and Habib, M.A. (1997). Investment appraisal in the public sector, *Oxford Review of Economic Policy* 13, 12–28.

Bunce, A.C. (1942). *Economics of Soil Conservation*. Iowa State College Press, Ames.

Burgess, D.F. and Zerbe, R.O. (2011). Appropriate discounting for benefit-cost analysis, *Journal of Benefit-Cost Analysis* 2, 1–20.

Cacho, O. (2001). An analysis of externalities in agroforestry systems in the presence of land degradation, *Ecological Economics* 39, 131–143.

Cacho, O., Greiner, R. and Fulloon, L. (2001). An economic analysis of farm forestry as a means of controlling dryland salinity, *Australian Journal of Agricultural and Resource Economics* 45, 233–256.

Caird, S., Robin, R. and Horace, H. (2008). Improving the energy performance of UK households: results from surveys of consumer adoption and use of low- and zero-carbon technologies, *Energy Efficiency* 1, 149–166.

Charles, A. (1983). Optimal fisheries investment: comparative dynamics for a deterministic seasonal fishery, *Canadian Journal of Fisheries and Aquatic Sciences* 40, 2,069–2,079.

Clark, C.W. (2010). *Mathematical Bioeconomics*. Wiley, New York.

Costanza, R. (2014). A theory of socio-ecological change, *Journal of Bioeconomics* 16, 39–44.

DairyNZ/DCANZ (2016). *Sustainable Dairying—Water Accord*. DairyNZ/DCANZ, Hamilton.

Deakin, M. (1999). Valuation, appraisal, discounting, obsolescence, and depreciation, *International Journal of Life Cycle Assessment* 4, 87–93.

Doole, G.J. (2015). A flexible framework for environmental policy assessment at the catchment level, *Computers and Electronics in Agriculture* 114, 221–230.

Doole, G.J. (2016). *Description of mitigation options defined within the economic model for the Healthy Rivers Wai Ora project*, Healthy Rivers Wai Ora report HR/TLG/2015-2016/4.6, Hamilton.

Dorfman, R. (1969). An economic interpretation of optimal control theory, *American Economic Review* 59, 817–831.

Durand, P., Moreau, P., Salmon-Monviola, J., Ruiz, L., Vertes, F. and Gascuel-Odoux, C. (2015). Modelling the interplay between nitrogen cycling processes and mitigation options in farming catchments, *Journal of Agricultural Science* 153, 959–974.

Dymond, J.R., Betts, H. and Schierlitz, C.S. (2010). An erosion model for evaluating regional land-use scenarios in New Zealand, *Environmental Modelling and Software* 25, 289–298.

Feder, G. and Umali, D. (1993). The adoption of agricultural innovations: a review, *Technological Forecasting and Social Change* 43, 215–239.

Felgenhauer, T. and Webster, M. (2014). Modelling adaptation as a flow and stock decision with mitigation, *Climatic Change* 122, 665–679.

Golder, P.N. and Tellis, G.J. (2004). Growing, growing, gone: cascades, diffusion, and turning points in the product life cycle, *Marketing Science* 23, 207–218.

Gotz, G. (2000). Strategic timing of adoption of new technologies under uncertainty: a note, *International Journal of Industrial Organisation* 18, 369–379.

Grepperud, S. (1997). Soil conservation as an investment in land, *Journal of Development Economics* 54, 455–467.

Grinter, J. and White, J. (2016). *National stock exclusion study: analysis of the costs and benefits of excluding stock from New Zealand waterways*, Ministry of Primary Industries Technical Report 2016/55, Wellington.

Hamilton, D.P., Salmaso, N. and Paerl, H.W. (2016). Mitigating harmful cyanobacterial blooms: strategies for control of nitrogen and phosphorus loads, *Aquatic Ecology* 50, 351–366.

Henderson, R.M. and Clarke, K.B. (1990). Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms, *Administrative Science Quarterly* 35, 9–27.

Hill, R. (2011). Sediment management in the Waikato region, New Zealand, *Journal of Hydrology* 50, 227–240.

Hill, M., Rowbottom, B. and Kaine, G. (2009). Understanding the benefits sought from grapevine nutrition management by Australian wine grape growers, *Extension Farming Systems Journal* 5, 63–72.

Iver, G., Hultman, N., Eom, J., McJeon, H., Patel, P. and Clarke, L. (2015). Diffusion of low-carbon technologies and the feasibility of long-term climate targets, *Technological Forecasting and Social Change* 90, 103–118.

Jaffe, A.B., Newell, R.G. and Stavins, R.N. (2004). Economics of energy efficiency, *Encyclopedia of Energy* 2, 79–89.

Kaine, G. and Bewsell, D. (2008). Adoption of integrated pest management by apple growers: the role of context, *International Journal of Pest Management* 54, 255–265.

Kaine, G. and Wright, V. (2017). *Rates of adoption and compliance in dairy farming*, Waikato Regional Council Technical Report 2017/6, Hamilton.

Kaine, G., Hill, M. and Rowbottom, B. (2008). *Types of agricultural innovations and the design of extension programs*, Department of Primary Industries Practice Change Research Working Paper 02-08, Tatura.

Kamien, M.I. and Schwartz, N.L. (1991). *Dynamic Optimisation: The Calculus of Variations and Optimal Control in Economics and Management*. Elsevier, New York.

Kuehne, G., Llewellyn, R., Pannell, D.J., Wilkinson, R., Dolling, P. and Ouzman, J. (2013). *ADOPT: The Adoption and Diffusion Outcome Prediction Tool* (Public Release Version 1.0, June 2013) [Computer software]. CSIRO, Adelaide.

Maani, K.E. and Cavana, R.Y. (2007). *Systems Thinking, System Dynamics: Managing Change and Complexity*. Pearson, Auckland.

McConnell, K.E. (1983). An economic model of soil conservation, *American Journal of Agricultural Economics* 65, 83–89.

Meade, N. and Islam, T. (2006). Modelling and forecasting the diffusion of innovation—A 25-year review, *International Journal of Forecasting* 22, 519–545.

Millner, A. and Dietz, S. (2015). Adaptation to climate change and economic growth in developing countries, *Environment and Development Economics* 20, 380–406.

Ministry for the Environment (MFE) (2017), *New Zealand's Environmental Reporting Series: Our Fresh Water 2017*. MFE, Wellington.

Moore, M.A., Boardman, A.E., Vining, A.R., Weimer, D.W. and Greenberg, D.H. (2004). 'Just give me a number!'. Practical values for the social discount rate, *Journal of Policy Analysis and Management* 23, 789–812.

Moreau, F. (2004). The role of the state in evolutionary economics, *Cambridge Journal of Economics* 28, 847–874.

Neill, S.P. and Lee, D.R. (2001). Explaining the adoption and disadoption of sustainable agriculture: the case of cover crops in northern Honduras, *Economic Development and Cultural Change* 49, 793–820.

O'Cass, A. (2000). An assessment of consumer product, purchase decision, advertising and consumption involvement in fashion clothing, *Journal of Economic Psychology* 21, 545–576.

Pannell, D.J. (2008). Public benefits, private benefits, and policy intervention for land-use change for environmental benefits, *Land Economics* 84, 225–240.

Pannell, D.J., Marshall, G.R., Barr, N., Curtis, A., Vanclay, F. and Wilkinson, R. (2006). Understanding and promoting adoption of conservation practices by rural landholders, *Australian Journal of Experimental Agriculture* 46, 1,407–1,424.

Pannell, D.J., Llewellyn, R.S. and Corbeels, M. (2014). The farm-level economics of conservation agriculture for resource-poor farmers, *Agriculture, Ecosystems, and Environment* 187, 52–64.

Park, W.G. (1994). Adoption, diffusion, and public R & D, *Journal of Economics and Finance* 18, 101–123.

Pennington, N. and Hastie, R. (1993). Reasoning in explanation-based decision making, *Cognition* 49, 123–163.

iPES Food (2016). *A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems*. iPES Food, Louvain.

Phillips, Y. (2014). *Non-market values for fresh water in the Waikato region: a combined revealed and stated preference approach*, Waikato Regional Council Technical Report 2014/17, Hamilton.

Reardon, T., Lu, L. and Zilberman, D. (2017). Links among innovation, food system transformation, and technology adoption, with implications for food policy, *Food Policy*. in press

Rogers, E.M. (2003). *Diffusion of Innovations*. Free Press, New York.

Sanford, W.E. and Pope, J.P. (2013). Quantifying groundwater's role in delaying improvements to Chesapeake Bay water quality, *Environmental Science and Technology* 47, 1,330–1,338.

Statistics New Zealand (SNZ) (2018), *Overseas Merchandise Trade Tables*. Statistics New Zealand, Wellington.
Syvitski, J.P.M., Vorosmarty, C.J., Kettner, A.J. and Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean, *Science* 308, 376–380.
Tang, K., Kragt, M.E., Hailu, A. and Ma, C. (2016). Carbon-farming economics: what have we learned?, *Journal of Environmental Management* 172, 49–57.
Thomsen, A.F. and van der Flier, C.L. (2011). Understanding obsolescence: a conceptual model for buildings, *Building Research and Information* 39, 352–362.
Ugray, Z., Lasdon, L., Plummer, J.C. and Bussieck, M. (2009). Dynamic filters and randomised drivers for the multi-start global optimisation algorithm MSNLP, *Optimisation Methods and Software* 24, 635–656.
United Nations Environment Program (UNEP) (2012). *Global Environment Outlook*. UNEP, Nairobi.
Varian, H.R. (1992). *Microeconomic Analysis*. Norton, New York.
Yalden, S. and Elliott, S. (2015), *Chlorophyll and visual clarity modelling of the Waikato and Waipa Rivers*, NIWA Client Report HAM2015-093, Hamilton.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Derivation of the investment rule (Eqn 6) dictating the optimal rate of diffusion.

Appendix S2. Description of the empirical model applied in Section 3.