# Valuing the effect of soil erosion on productivity

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## Abstract

Soil erosion is a significant environmental issue in New Zealand. Erosion reduces soil fertility, land productivity, water quality, and biodiversity, among other impacts. Although several studies have been conducted to assess the physical damage that erosion could pose on crop and forest productivity, there is a lack of research into the monetary value of this damage. In this study, we employ a bio-economic analysis to estimate the monetary value of productivity loss due to soil erosion. The analysis integrates spatially explicit information on soil erosion and farm revenues alongside potential productivity loss rates due to soil erosion. The results show that the mean marginal cost of erosion (cost of one tonne per year) is estimated at $1.2 with a minimum of $0.003 and maximum of approximately $4. The impact of erosion is highly dependent on land use, and our analysis illuminates some important variation in the underlying factors. Our findings also show that the marginal cost of surficial erosion is higher than the marginal cost of mass movement erosion. Our results could ultimately be used to provide aggregated cost estimates for soil erosion at the national, regional or catchment level. By illuminating important costs and tradeoffs, these estimates should be a significant contribution to governmental planning and analysis related to mitigating the adverse impacts of soil erosion.

### Keywords

Erosion, impact assessment, productivity loss, policy analysis, New Zealand

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# Introduction

Over the last few decades, New Zealand has been facing elevated erosion rates across different types of landscapes. These high erosion rates could lead to a wide range of impacts on our environment, economy and communities. These include reductions in soil fertility, land productivity, water quality, and biodiversity, among others. Since agriculture comprises a significant share of New Zealand's economy, the impacts of erosion on land productivity have drawn considerable attention from policy makers and landowners. The impacts of declining land productivity are not only reflected as lower farm incomes but also lower demand on the services offered by downstream industries, and subsequently lower profits along the whole supply chain.

Previous studies have focused on analysing the relationship between crop productivity and soil characteristics, management practices, and climatic conditions. For instance, Hicks (1995) showed the severity of reductions in crop and pasture yield that could be caused by erosion. Although these studies have improved our understanding of how eroded soils could affect land productivity, there is still a lack of research on the monetary value of such losses, especially for marginal changes. From a policy making perspective, it is crucial to be able to value changes in erosion to evaluate tradeoffs between different policy approaches and allocate a suitable budget to managing it. In this analysis, we aim to quantify and monetise losses in productivity due to soil erosion and to show how these losses could differ across landscape. We combine several novel and spatially explicit datasets to illustrate the analysis of productivity loss using a case study.

# Background and Literature

Soil erosion is a widespread problem in New Zealand, with rough analysis suggesting its impact could be at least $300 million per year.[1] There is a large amount of both natural and human-induced erosion, with the latter exacerbated by widespread conversion of area to pasture lands (Basher et al. 2016). Erosion control has attracted significant research interest and policy attention over the last few decades (Blaschke et al. 2008; Barry et al. 2014; Fernandez 2017; Basher et al. 2019) as the direct and indirect costs become more apparent. There is also concern that climate change will make the impacts of soil erosion worse, as weather and rainfall patterns change (Nearing et al. 2004; Mullan et al. 2012). Although erosion has a number of other impacts on the environment, we focus here in productivity-related impacts.

Soil erosion can affect productivity in a number of important ways (Dregne 1995), including impacts on rooting depth, losses of nutrients and soil carbon, changes in available water, changes in the density of soil, changes in land area, damages to seedlings, and growth cycles (Lal 1998). Each of these impacts can vary significantly, depending on local landscape features and the type of crop grown (Lal & Moldenhauer 1987). Although some of these effects can be mitigated, they also carry significant costs. For instance, some of the loss of soil nutrients can be countered by applying fertilizer and manure. However, this can be costly, and can have quickly diminishing returns if the

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[1] https://www.rnz.co.nz/news/national/387424/erosion-is-costing-nz-up-to-300m-a-year. Accessed August 2020.

subsoil is already degraded.[2] In addition, excess fertilizer is associated with other environmental externalities like water quality impacts

# Materials and Methods

## *Analytical framework*

We develop an approach for monetising marginal changes in erosion and demonstrate their utility using a case study. This analysis focuses on the Fordell-Kakatahi area, which is located in the Wanganui district, part of the Manawatū-Whanganui region (Fig 1). In order to quantify and monetise losses in productivity from soil erosion, we integrated spatial information on erosion rates, erosion-related productivity losses, and farm income. Spatial information on erosion rates was sourced from the SedNet model, which is a catchment scale GIS-based model (Dymond et al., 2016). It estimates several different types of soil erosion, which are measured as tonnes per $km^2$ per year. Erosion consists mostly of surficial and mass movement erosion, where mass movement erosion includes landslides, gullying, and earthflows. The model is also capable of tracing the amount of sediment that ends up in streams and rivers, as well as the effect of management practices on sediment loads.

[2] Additional information can be found at https://crops.extension.iastate.edu/encyclopedia/soil-erosion-effect-soil-productivity.

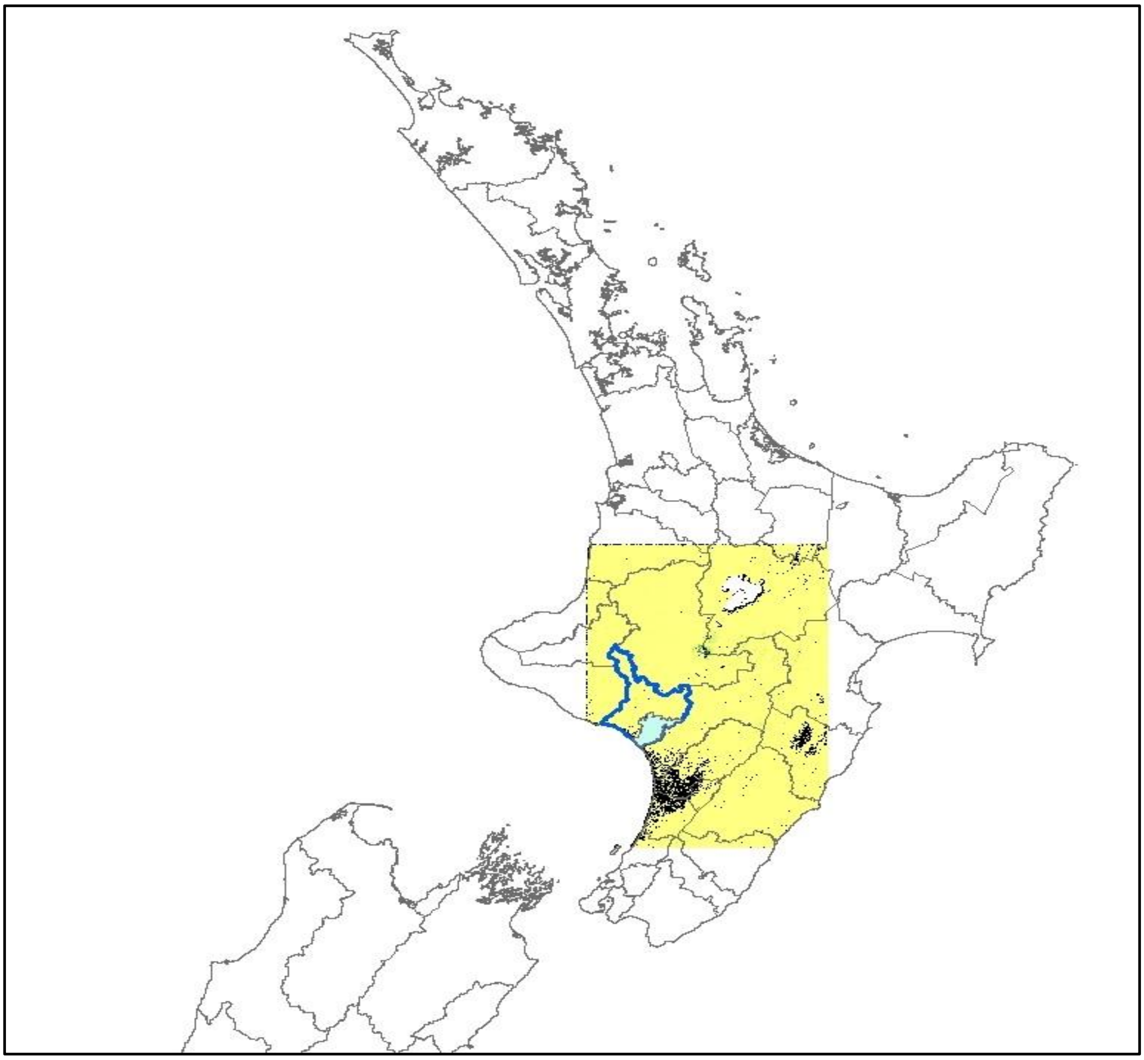

Figure 1. The study area of the analysis Fordell-Kakatahi. The yellow area is the area that has been modelled by SedNet to date. The light blue area is the area that was used in our analysis (Fordell-Kakatahi) which is located in the Wanganui district (highlighted by dark blue boarder).

Farm incomes were obtained from the NZFARM model (Daigneault et al., 2018). The model utilises a land use map alongside location-based information on farm budgets (production, output prices, input costs) to estimate net revenues per farm type in each location. Unfortunately, information on productivity losses due to soil erosion is scant in New Zealand. One notable study that summarises previous research is Hicks (1995), who summarise the range of potential production losses for each erosion type (Table 1).

**Table 1. Range of percentage reductions in crop and pasture yield due to erosion***

| Erosion process | Minimum reduction (%) | Maximum reduction (%) |
|---|---|---|
| Surface erosion, cropland | 0 | 62 |
| Surface erosion, pasture | 0 | 78 |
| Surface erosion, tussock | 0 | 93 |
| Deep mass movement, pasture (initial) | 0 | 77 |
| Deep mass movement, pasture (re-grassed) | 0 | 77 |

| | | |
|---|---|---|
| Shallow mass movement, pasture (initial) | 0 | 80 |
| Shallow mass movement, pasture (re-grassed) | 0 | 42 |

*Adapted from Hicks (1995)

Another notable study in New Zealand is an analysis done by Heaphy (2013), who assessed the impact of soil erosion on the productivity of *Pinus radiata* trees in the Hawke's Bay region. In his field experiment, 15 plots of exotic *Pinus radiata* trees were planted in marginal land that is exposed to landslide erosion. The productivity of these plots was then compared to other plots that were planted on non-eroded land. The results showed that the trees on the eroded soil produced 16% less volume than those that are planted on non-eroded soil.

### *Linking erosion to productivity and profitability loss*

In order to convert the erosion rates into productivity loss and subsequently into profitability loss, we used a two-step process. In the first step we convert erosion rates into productivity loss and in the second step we convert productivity loss into profitability loss. To convert erosion rate to productivity loss, we used a decision tree rescaling rule that is based on the data provided by Hicks (1995) and Heaphy (2013). In this decision tree, we assumed that:

- For farm types classified as cropland (i.e. arable, vegetables, and fruit), productivity loss will range between 0-62% for surficial and mass movement erosion;
- For farm types classified as pastoral land (i.e. dairy, sheep and beef, deer and other pasture), productivity loss will range between 0-78% for surficial erosion and between 0-69% for mass movement erosion;
- For farm types classified as forest (i.e. native or exotic forestry), productivity loss will range between 0-30% for surficial erosion and between 0-44% for mass movement erosion. The mean for both ranges was assumed to be 16% (Heaphy 2013).

In the second step, we assumed that there is a linear (1-to-1) relationship between productivity and profitability loss (O'Donnell, 2010). This simple assumption should allow a demonstration of the model, with more complicated relationships between productivity and profit explored later.

# Results

In this section we show the outputs for farm incomes and the distribution of surficial and mass movement erosion in the Fordell-Kakatahi area. We also show the cost of erosion (the sum of surficial and mass movement erosion) which is the outcome of merging farm incomes, surficial and mass movement erosion, and their estimated impacts on productivity and profitability.

### *Farm incomes*

The main land uses in the Fordell-Kakatahi area are sheep and beef (42%), exotic pine forestry (27%), arable (11%), native trees (10%), and dairy (4%) (Table 2). However, most of the region net income is generated from arable land ($8.5 million), exotic forestry ($7.5 million), and dairy ($5.7 million). This is because the average net income of one hectare of dairy (~$3200), arable ($1600), and exotic forestry (~$600) is much higher than net revenues from one hectare of sheep and beef ($8).

**Table 2. Landuse and net revenue (EBIT) of the Fordell-Kakatahi (Wanganui) area**

| Land use | Total Area (Ha) | Average EBIT ($/Ha) | Total EBIT ($) |
|---|---|---|---|
| Arable | 5,170 | 1,650 | 8,530,500 |
| Dairy | 1,789 | 3,208 | 5,739,112 |
| Deer | 207 | 586 | 121,302 |
| Exotic forestry | 12,332 | 612 | 7,547,184 |
| Fruit | 86.6 | 7,406 | 641,360 |
| Native forest | 4,368 | 0 | 0 |
| Other | 2,134 | 0 | 0 |
| Other pasture | 85.8 | 17.1 | 1,467 |
| Sheep & beef | 19,188 | 7.63 | 146,404 |
| Vegetables | 9.96 | 9,356 | 93,186 |

Figure 2 shows that the northern part of the Fordell-Kakatahi area is mainly covered by forestry, while the southern part of the area is covered by vegetables, fruits, and arable land. The middle area has livestock farming as the major land use.

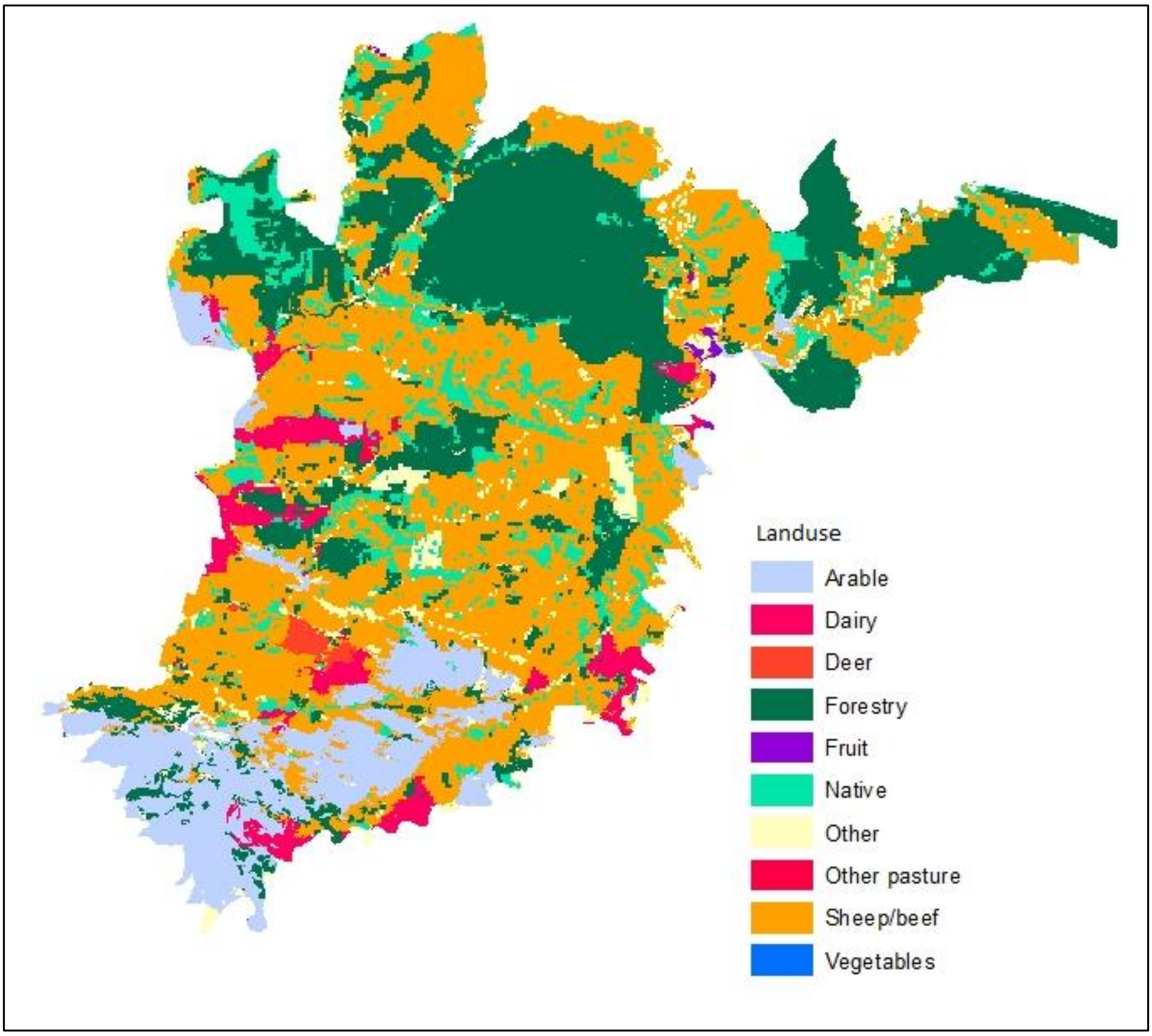


Figure 2. The spatial distribution of land uses in the Fordell-Kakatahi area. The reddish/orange colour area represents livestock farms, bluish area represents horticulture and arable land, and the greenish area represents exotic and native forestry.

## *Erosion*

Using the SedNet model we generated the spatial pattern of the surficial erosion in the Fordell-Kakatahi area. Results show that erosion rates are higher at the middle, Northern, and Northwest parts of the area (Fig 3). The overall surficial erosion rates in this region were relatively low, mostly within the 5 percentile of the North island range of surficial erosion (except for some outliers).

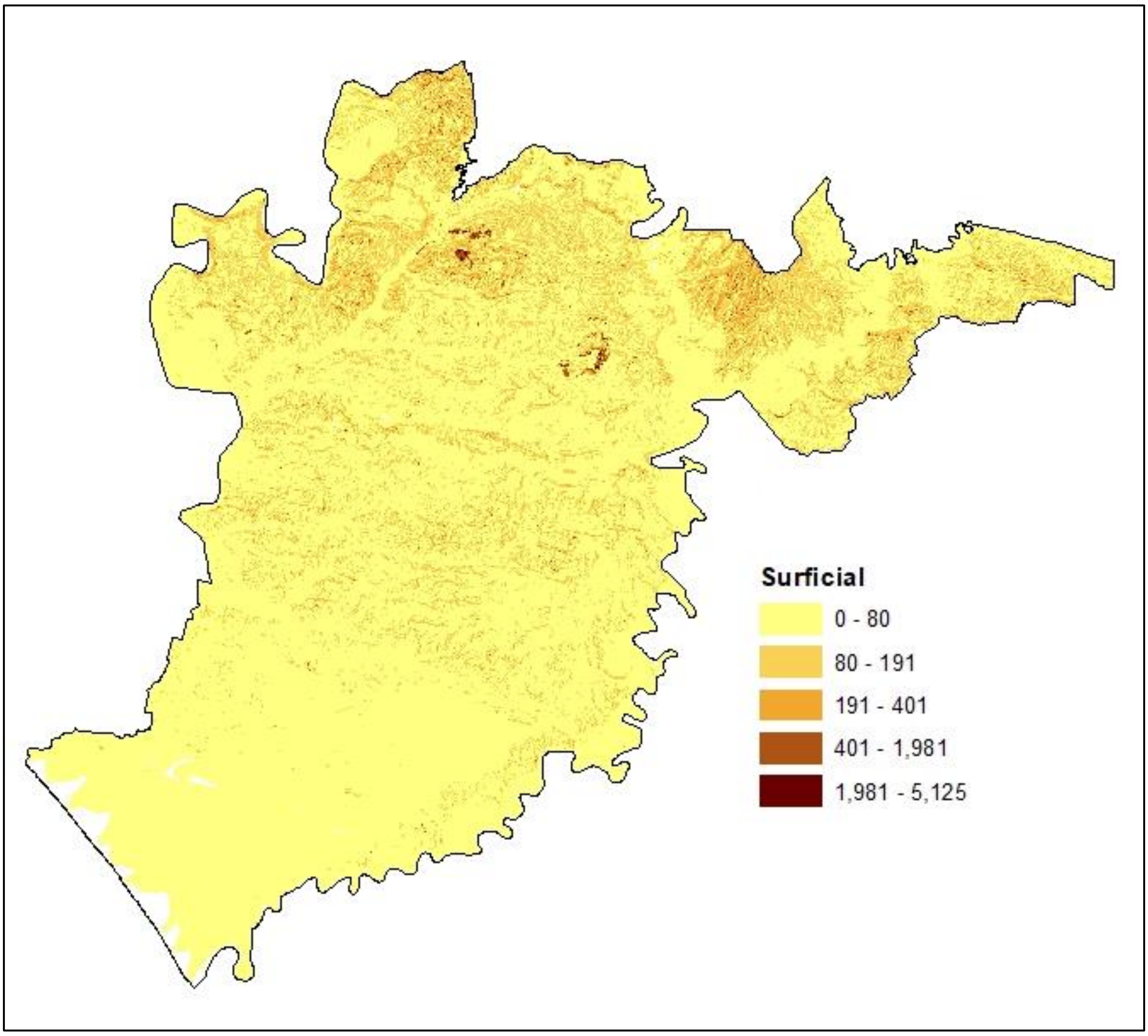


Figure 3. The spatial distribution of surficial erosion in the Fordell-Kakatahi area (tonne per $km^2$ per year).

Mass movement erosion consists of landslide, gully, and earthflow erosion. Figures 4, 5, and 6 show the distribution of landslide, gully, and earthflow erosion in the Fordell-Kakatahi area, respectively. Landslide erosion is estimated to cover large parts of the middle and northern parts of the Fordell-Kakatahi area. In contrary, gully erosion was limited only to the northern areas while earthflow erosion was limited to small areas in the middle of Fordell-Kakatahi.

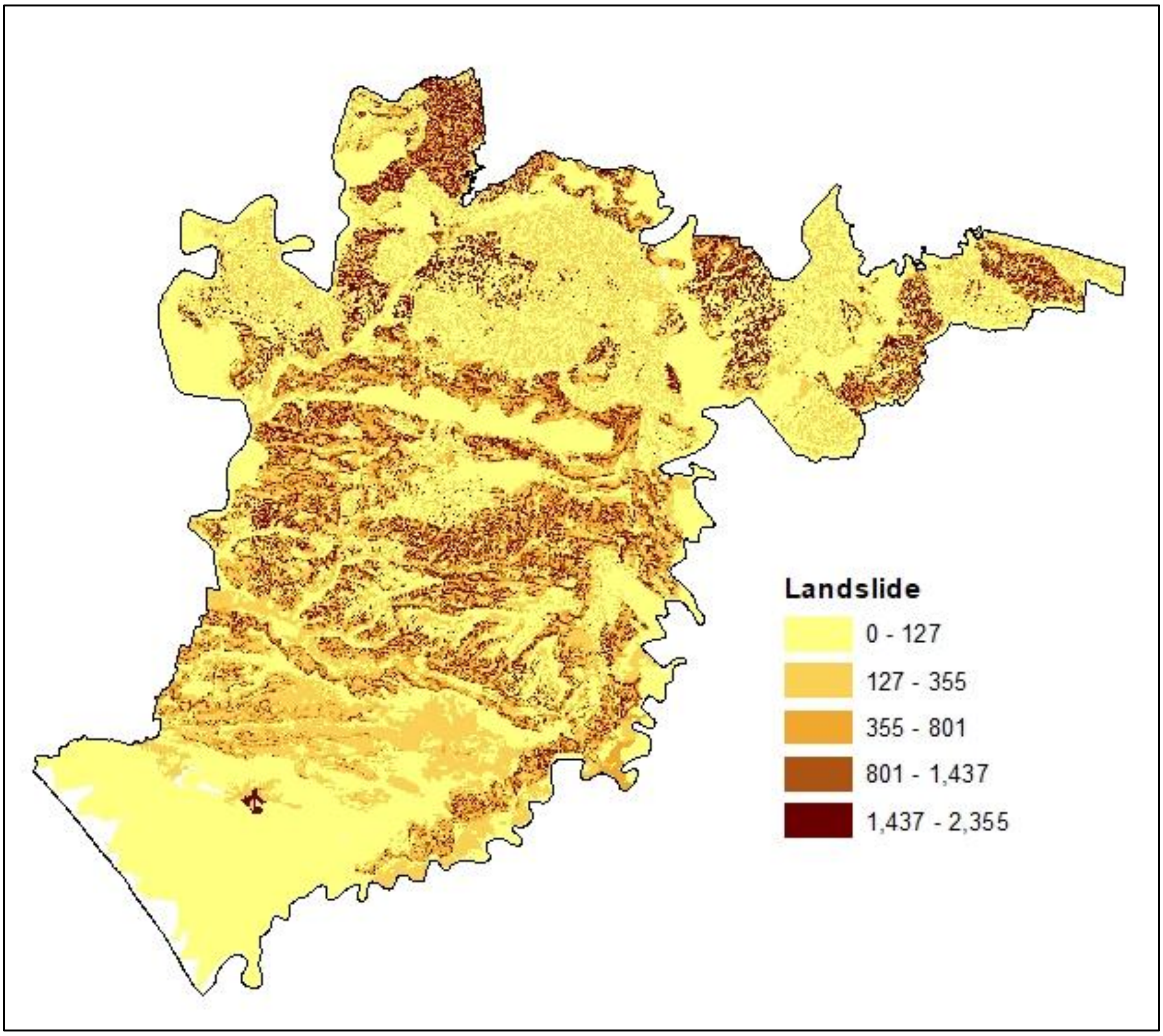


Figure 4. The spatial distribution of the landslide erosion in the Fordell-Kakatahi area (tonne per $km^2$ per year).

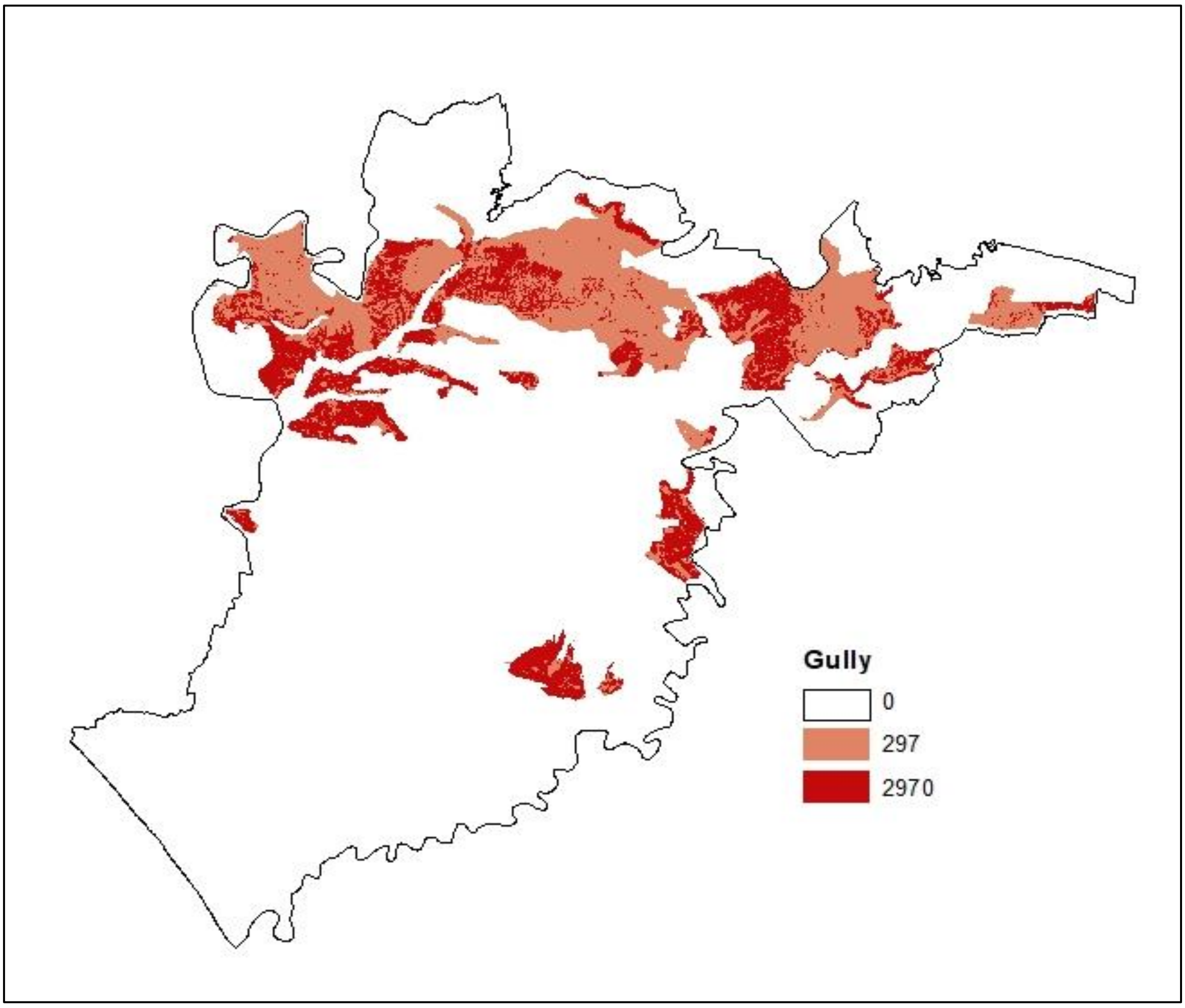


Figure 5. The spatial distribution of Gully erosion in the Fordell-Kakatahi area (tonne per km$^2$ per year).

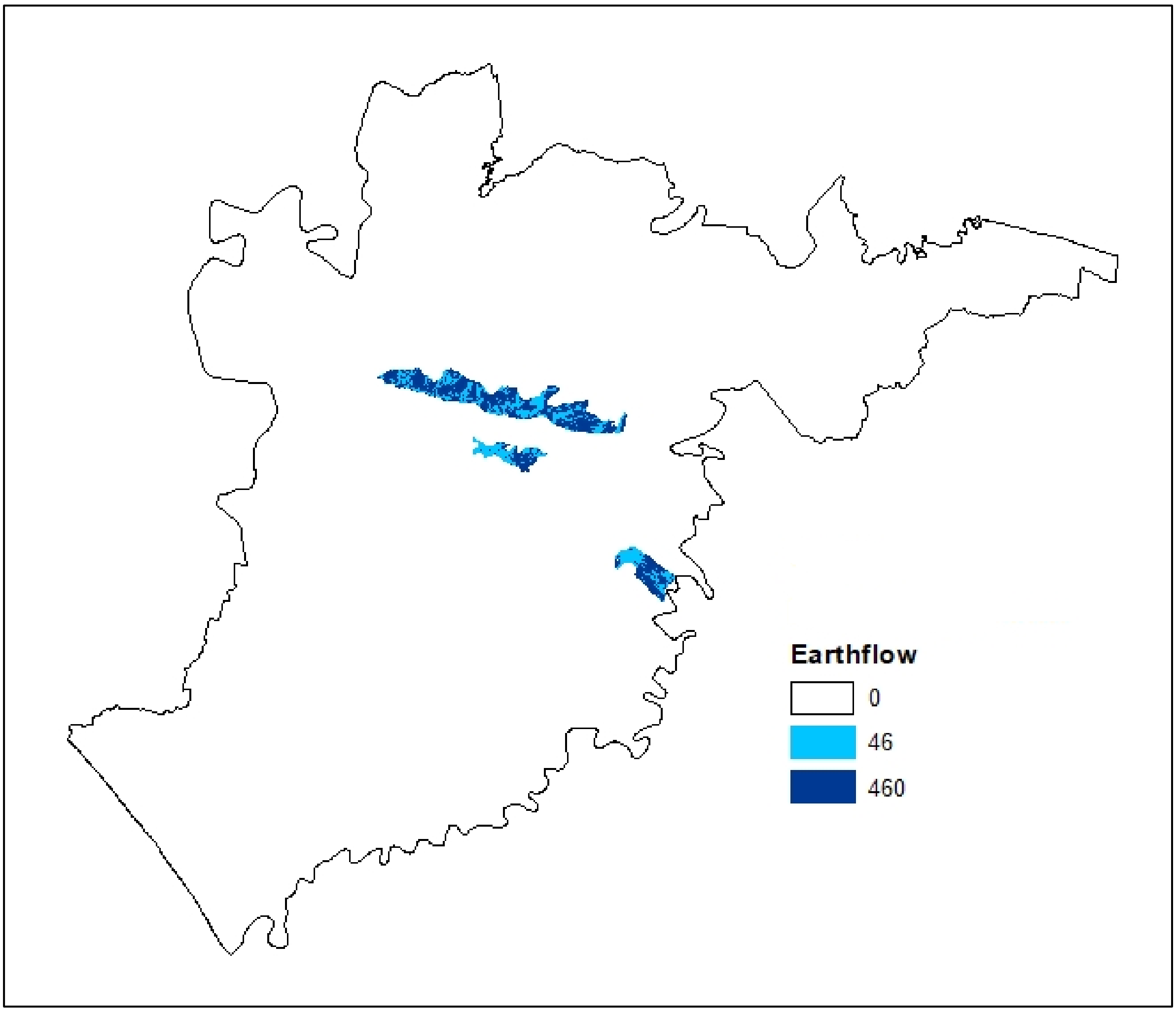


**Figure 6. The spatial distribution of earthflow erosion in the Fordell-Kakatahi area (tonne per km$^2$ per year).**

## *Cost of erosion*

After integrating the erosion data with land use and productivity maps, results show that the highest marginal cost of surficial erosion is found in vegetables, fruit, and dairy, while the lowest marginal cost of surficial erosion is in exotic forestry, sheep and beef, and other pasture (Table 3). The high surficial erosion cost for horticulture is mainly driven by the high annual net revenues (7k-9k/ha). Sheep & beef, and exotic forestry are often located in marginal land with relatively low annual net revenues, so the marginal impact of erosion is low. For the Fordell-Kakatahi area, the per hectare annual net revenues for sheep & beef was estimated at approximately \$8, with exotic forestry at \$600.

Similar to the estimates for the cost of surficial erosion, the highest marginal cost of mass movement erosion was in vegetables (\$1.2 per tonne) and fruit (\$0.89 per tonne), while the lowest marginal cost of mass movement erosion was in sheep & beef and other pasture farms (estimated at \$0.001 per tonne and \$4.7e$^{-05}$ per tonne, respectively).

By adding the marginal cost of surficial and mass movement erosion, we get the marginal cost of total erosion. The results show that the mean cost of one tonne of erosion is estimated at $1.2 with a minimum of $0.003 and maximum of approximately $4 (Table 3 and Fig. 7). Our findings also show that the marginal cost of surficial erosion is higher than the marginal cost of mass movement erosion. This is because mass movement processes have resulted in larger amounts of eroded soil than those generated from the surficial processes. As we assume quite similar crop damage rates for both types of erosion, this assumption, alongside the higher eroded soil rates from mass movement, resulted in lower marginal costs for mass movement erosion as compared to surficial erosion.

**Table 3. The (mean) marginal cost of total erosion (surficial and mass movement) by farm type ($/tonne)**

| Farm type | Marginal cost of Erosion ($/tonne) | | |
|---|---|---|---|
| | **Surficial** | **Mass movement** | **Total** |
| Arable | 0.49 | 0.19 | 0.69 |
| Dairy | 1.22 | 0.42 | 1.64 |
| Deer | 0.22 | 0.07 | 0.29 |
| Exotic forestry | 0.09 | 0.05 | 0.13 |
| Fruit | 2.22 | 0.89 | 3.11 |
| Native | 0 | 0 | 0 |
| Other | 0 | 0 | 0 |
| Other pasture | 0.01 | 0 | 0.01 |
| Sheep & beef | 0.003 | 0.001 | 0.003 |
| Vegetables | 2.81 | 1.12 | 3.93 |

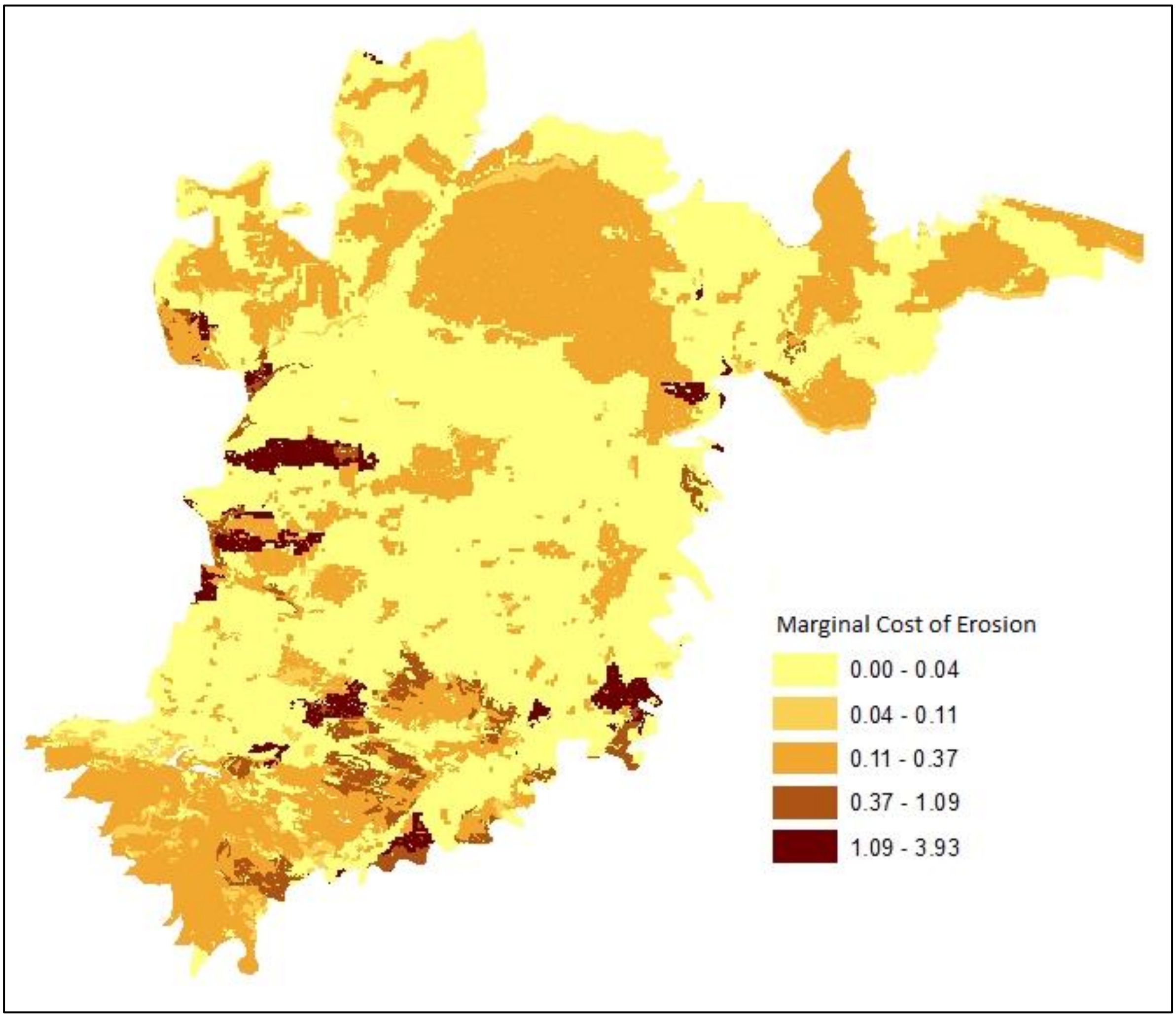


Figure 7. The spatial distribution of the marginal cost of total erosion in the Fordell-Kakatahi area (dollar per tonne)

# Conclusion and limitations

This paper demonstrates methods for estimating an important component of the monetary cost of erosion by focussing on the productivity impacts of surficial and mass movement erosion. By integrating spatial information on soil erosion, farm net revenues, and potential productivity losses, we were able to spatially estimate (in monetary terms) the cost of erosion due to productivity loss. The results show that the marginal cost of erosion ranges between $0.003 - $3.93 per tonne with a mean value of $1.2 per tonne. The marginal cost of erosion has also been estimated by farm type. By integrating this information (cost of one tonne of erosion per farm type) with the erosion and land use maps of New Zealand, we can extrapolate our findings to generate a national map that represents the cost of total erosion ($ per hectare).

Due to data limitations, some of the functional relationships in our analytical framework were simplified. For instance, we assumed that the productivity-profitability relationship is one-to-one (i.e. linear). This might not be the case for some agricultural commodities as there are other factors in the production function that might affect the profits (e.g. cost of inputs and output prices that could differ across different scales of production). Although this allows us to demonstrate some of the main relationships, future research will focus on using more advanced linking functions. The chosen area of study also does not have many areas of extreme erosion. However, even with fairly low rates of erosion, our results suggest that there may still be notable costs.

This study represents the first analysis of the marginal cost of erosion on productivity in New Zealand. The results should be useful in benefit cost analyses of erosion control, and provide important information for targeting erosion control measures.

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