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RESEARCH

Flood Impacts on Agriculture under Climate Change: The case of the Awanui Catchment, New Zealand

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Abstract

We assess the economic and environmental impacts on agriculture of flooding under projected climate change, including land-use change as an adaption response to floods. Our case study area is the Awanui catchment located in the far north of New Zealand, where flooding is a significant hazard. The study uses an integrated approach and combines spatial information on agricultural exposure and damage from flooding, economic land-use modelling, and valuation approaches. We analyse direct tangible and direct intangible flood impacts under various extents, frequencies, and water depth levels. Our results show areas with flood exposure and damage costs increase with projected climate change. As an adaptation measure to reduce flood damage costs, pastoral farms convert to other land uses, mainly to unfarmed land. Flooding reduces the net revenue for the catchment, while it can result in some reduction of environmental pollution. When the probability of all possible flood events are considered, the value of the changes in greenhouse gas emissions are equivalent to approximately 18% of the change in total net revenue, while the value of changes in other environmental outputs is equivalent to less than 1% of the change in total net revenue. Based on this study, the assessment of various flood impacts and adaptation responses to them can help to develop resilience strategies for the agricultural sector to future climate-induced flooding.

Keywords Climate change adaptation · Flood risk · Integrated analysis · Natural disasters · Tangible impacts · Intangible impacts

1 Introduction

Floods are among the costliest natural disasters in the world, costing US$300 billion globally between 2018 and 2022 of which roughly US$45 billion was insured (Munich Re 2022). In recent decades, an increase in flood damage has been observed (UNDRR 2020), and it is expected that the frequency and severity of floods will further increase with climate change (IPCC 2023). The agricultural sector is especially vulnerable to floods, and flood damages cause substantial economic losses to the agricultural sector (English et al. 2021; FAO 2021; Koç et al. 2021).

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Losses in the agricultural sector are driven by various flooding parameters, including extent, frequency, water depth, inundation duration and seasonality, and flow velocity (Nga et al. 2018; Brémond et al. 2013). In addition, floods can have different types of impacts on the economy of the agricultural sector, including direct tangible, direct intangible, indirect tangible, and indirect intangible impacts (Merz et al. 2010). The direct tangible impacts of floods on individual farms were estimated to cost up to NZ$890,000 during the 2017 Bay of Plenty floods in New Zealand and included flood inundation of farms that damaged crop and livestock production and capital assets (Paulik et al. 2021). Floods can also have direct intangible impacts on agriculture by impacting environmental conditions at farms. For instance, flooding can increase cumulative N_2O emissions from grasslands by 97 times and CH emissions by 1.6 times by disrupting carbon cycling (Oram et al. 2020). The indirect tangible impacts of floods can disrupt other business activities outside the flooded area (Carrera et al. 2015), while indirect intangible impacts can lead to psychological trauma for farmers (Merz et al. 2010).

Adaptation of farm practices such as changing crop types, crop diversification, planting trees and leaving agricultural fields idle are one of the key strategies to reduce the negative impacts on agricultural production of increasing extreme weather events with climate change (Thennakoon et al. 2020). In the case of the lower South Island of New Zealand, Griffin et al. (2023) reported that farmers pursue smaller-scale, regenerative and diversification farming as options to adapt to flooding and climate change. Floods impact farm practices by directly reducing production and by causing a land-use change from more vulnerable land uses to less vulnerable (Nguyen et al. 2022). For instance, Nguyen et al. (2022) showed that farmers in Vietnam abandoned their croplands to reduce flood damage costs. Using an integrated impact assessment, Brouwer and van Ek (2004) in the case of the Netherlands showed that land-use change is a viable measure to reduce flood damages when considering its environmental and economic benefits. Changes in agricultural land use can reduce the financial repercussions of floods (WMO 2009) while also affecting environmental indicators such as water quality, biodiversity, soil erosion, and GHG emissions (Wheater and Evans 2009). Therefore, farmers facing flood events need to plan adaptation measures while considering changes in environmental outputs as a result of adaptation, as well as agri-environmental policies that regulate these environmental outputs.

Disaster risk management requires reliable estimates of the potential economic damages caused by floods and also of the costs of adaptation responses needed to prevent huge flood losses with expected climate change (UNDRR 2020). Several efforts have been made to assess flood impacts on the agricultural sector considering various flood damage costs (e.g. Scorzini et al. 2021; Nga et al. 2018; Jonkman et al. 2008) and adaptation responses to flooding (e.g. Nguyen et al. 2022; Cradock-Henry et al. 2019; Manning et al. 2015). Previous research applied different methodologies, including post-event surveys (Nguyen et al. 2022), financial damage cost analysis (Yildirim and Demir 2022; Nga et al. 2018; Klaus et al. 2016), econometric models (Heinen et al. 2019; Cunado and Ferreira 2014), and economic simulation models (English et al. 2021; Dottori et al. 2018; Carrera et al. 2015). Each of these methodologies has its advantages and disadvantages. With sufficient data, post-event surveys and econometric models can quantify flood impacts with a high level of accuracy (Nguyen et al. 2022; Wagenaar et al. 2016). However, they are based on observed data and make interpolations of these data to estimate the flood damage costs. These estimations cannot assess the impacts of unobserved events like flooding under projected climate change on the agricultural system, where economic and environmental outputs and adaptation responses of farmers simultaneously change due to these impacts. Similarly, financial cost-benefit analyses cannot assess the simultaneous changes of different indicators in the agricultural system as a result of new flood events. Alternatively, economic simulation models can assess the systematic changes in agriculture as a result of flooding under projected climate change.

Few studies considered impacts of floods on agriculture under projected climate change, by considering simultaneously different flood parameters, impacts and adaptation responses using simulation modelling (e.g. Scorzini et al. 2021; Brouwer and van Ek 2004). As a result, the economic impacts of floods under projected climate change and adaptation responses to floods on agriculture are poorly understood.

We aim to analyse the economic and environmental impacts of flooding under projected climate change on agriculture and forestry and consequent adaptation responses in terms of land-use change. Due to focus of our research, we do not analyse the economic costs of flooding on residential houses, businesses, transportation and other sectors of the economy. Our case study is located in the Awanui catchment, New Zealand. In New Zealand, floods have caused in total more than NZ$2.9 billion in insurance claims between 2015 and 2023, which included claims for flood damages affecting the residential housing and contents, businesses, motor vehicles, marine, agriculture and other sectors of the economy (ICNZ 2024). The IPCC's projections adapted to New Zealand indicate we will see an increase in extreme rainfall, which should increase the frequency and intensity of floods (IPCC 2021). Our study integrates spatial analysis of land use and flood hazard, economic land-use modelling, and valuation of environmental outputs. We analyse direct tangible and direct intangible impacts of flooding under different extents, frequencies, and water depth levels on agriculture and forestry. We map the agricultural sector land-use areas exposed to flooding, as well as modelling changes in agricultural and forestry net revenues, land-use area, and environmental outputs.

2 Methods

The research methodology for this analysis comprised three key components, as illustrated in Fig. 1. First, we employed the RiskScape software engine (Paulik et al. 2022) to combine spatial data about agricultural and forestry exposure to flooding and compute the resulting damages for each farm (refer to Section 2.2 for details). Second, we integrated this spatial flood exposure data into an economic land-use model known as the New Zealand Forest and Agriculture Regional Model (NZFARM; Daigneault et al. 2018). This allowed us to examine how floods impact potential land-use changes at agriculture and forestry, and the subsequent alterations in economic and environmental indicators (see Section 2.3 for further information). Finally, we used economic valuation methods to evaluate the changes in environmental outputs resulting from land-use changes induced by changes in flood patterns (see Section 2.4).

2.1 Study area

We undertook our analysis in the Awanui catchment, located in the Far North District of the Northland Region in New Zealand (Fig. 2). Flooding has been identified as a significant hazard in the catchment (DHI Group 2020).

The catchment area is about 456 km^2, where the southeast of the catchment is mostly steep terrain but becomes flatter following the flow direction towards the north and west. For instance, between the town of Kaitaia and the Ranganu Harbour, the elevation drops

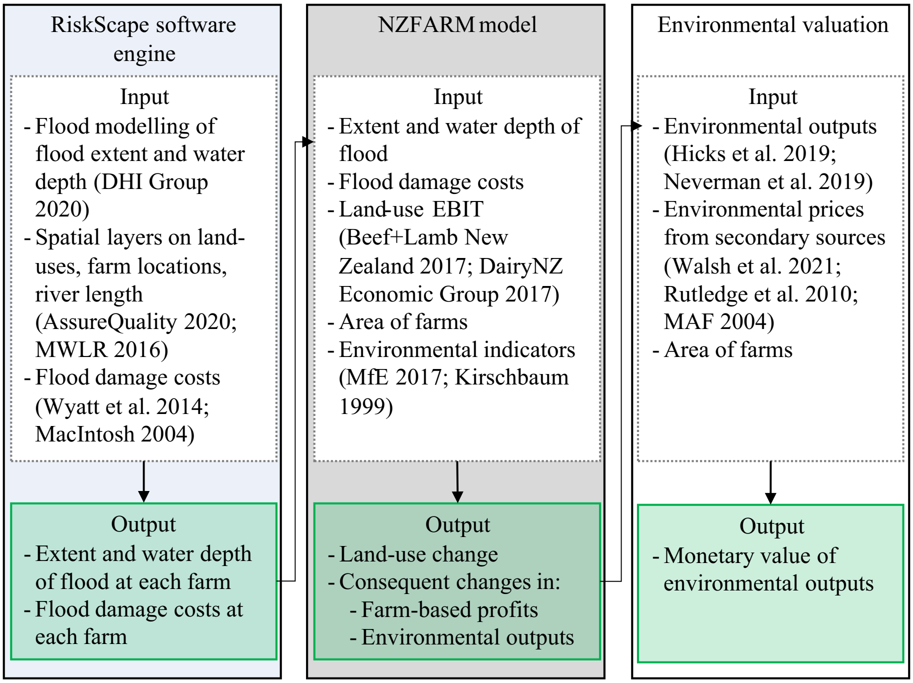

Fig. 1 Methods used to analyse the impact of floods on the primary sector. Note: EBIT is Earnings Before Interest and Taxes. In brackets are indicated some of the data sources. The complete list of data sources and their assumptions are given in Sections 2.2, 2.4 and 2.6

by 14 m over a 12-km distance: from 15 m to 1 m above sea level (DHI Group 2020). The highest elevation in the catchment is 730 m above sea level at the steep headwaters. The Awanui River is fed by several tributaries, including the Takahue River, Victoria River, Karemuhako River, and Tarawhataroa Stream.

The population of the catchment as of the 2018 census is 10,896 individuals living in 3,150 households. Approximately 60% of the population is Māori.[1]

The major land uses of the primary sector in the catchment are dairy, sheep and beef, other pasture, forestry, fruits, vegetables, and unfarmed land.[2] The total area of agricultural and forestry land uses in the analysis is approximately 345 km^2, with the remainder of the area mainly in residential and lifestyle farms. Some 465 farms are included in the analysis, differentiated by their land use, area, and location in the catchment. Sheep and beef farming is the largest primary sector land use in the catchment, followed by dairy farming (see Table 9 in Appendix 1). Other flooded land uses (e.g. buildings, lifestyle farming, and native vegetation) are out of the scope of this analysis.

[1] Māori are the indigenous people of New Zealand.

[2] Unfarmed land is land on a farm that is idle or is not being used for agriculture or forestry production.

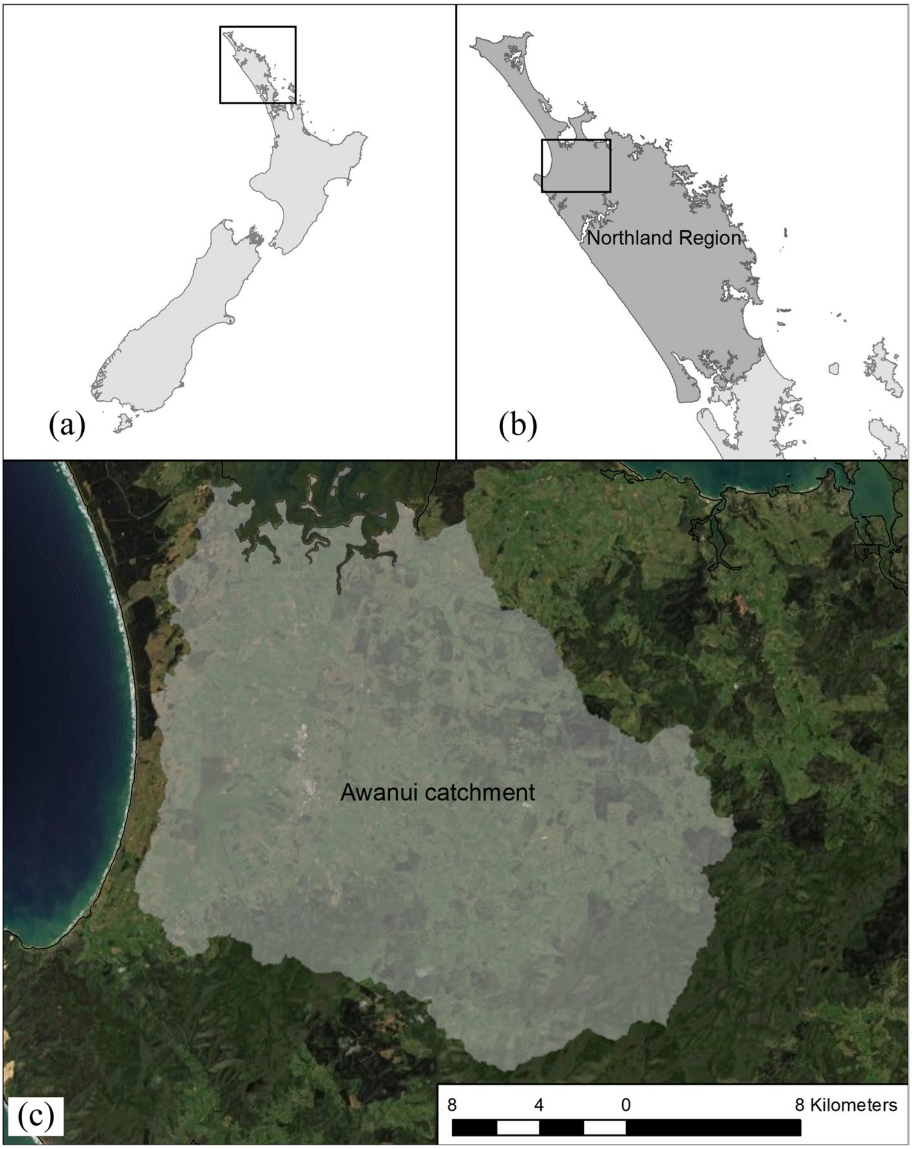

Fig. 2 Awanui catchment. **a** Location of study area in New Zealand; **b** Location within region; **c** Location of catchment boundaries

2.2 Spatial Extent and Costs of Flood

We used the RiskScape software engine (Paulik et al. 2022) to combine and calculate agricultural and forestry exposure (Section 2.2.1) and damage from flooding (Section 2.2.2) for each farm and calculate the areas exposed to flood, their water depth levels, and the costs for each of these land uses using the spatial layers. To calculate possible extent and costs of flooding on current land uses without adaptation measures, we assumed the observed (current) land-use pattern remains in both the present-day and with climate change. We annualise the expected production losses and repair costs of land uses for different magnitude flood events.

2.2.1 Average Recurrence Interval

To calculate the areas exposed to flood and water depth levels for each farm in the catchment, we used the Awanui catchment flood modelling by DHI Group (2020). The model of frequency and 24-hour depth of rainfall events was derived from historical rain gauge records in the catchment. This model was used to develop four present-day rainfall scenarios: 24-hour events with Average Recurrence Intervals (ARIs) of 10 years, 20 years, 50 years, and 100 years. For climate change scenarios, DHI Group (2020) assumes a 2.1 °C temperature increase alongside a 1-m rise in sea level. The closest IPCC Representative Concentration Pathway (RCP) scenario was RCP4.5. The impact of a 2.1 °C temperature increase on rainfall was estimated using the historic 24-hour rainfall depth by ARI and the projection factors published in Carey-Smith et al. (2018). The rainfall was increased by 17.01% for the 10-year ARI, 17.22% for the 20-year ARI, 17.64% for the 50-year ARI, and 18.06% for the 100-year ARI. The tidal boundary increased by 1 m from the present-day tidal boundary.

The extents and depths of floods for each ARI for present-day and climate change scenarios were modelled using the 2017 release of MIKE FLOOD software (Service Pack Two).[3] MIKE FLOOD by DHI software is specifically designed for flood modelling and analysis in river basins, urban areas, and coastal regions. It offers a range of tools and capabilities to simulate hydrological processes, rainfall-runoff mechanisms, hydraulic flow behaviour, and flood inundation patterns. The model uses topography, soil, land cover, and the existing flood management schemes to predict flood extent and depth in each location.

When analysing flood impacts, we assumed that flood events at each ARI occur in a single year and do not have dynamics over time because of insufficient information on the dynamic impacts of floods. Also, due to insufficient data, inundation duration, seasonality, and flow velocity parameters were not included.

Table 1 presents the area flooded categorised by six discrete flood water depth levels: 0.0–0.5 m, 0.5–1.0 m, 1.0–1.5 m, 1.5–2.0 m, 2.0–2.5 m, and greater than 2.5 m. Most of the flooded area is flooded to a depth of 1.5 m or less. Compared with the present-day scenario, under the climate change scenario, both flooded areas and depth are projected to increase. There is less area flooded at the lowest water depth levels (0.0–0.5 m) with climate change, but more land flooded with deeper water depths than in the present-day. While the 10-year ARI floods cover the smallest areas, they occur more frequently than the other ARI flood events.

We used the spatial information of ARIs in the present-day and projected climate change to layer them with the spatial information on agricultural land area and use categories and farm boundaries within the Awanui catchment (AssureQuality 2020; Newsome et al. 2018; MWLR 2016). Depending on the location of farms and the extent of ARIs, the farms can be partially or fully exposed to flooding under different water depth levels.

Figure 4 in Appendix 2 shows the extent and depth of floods in 10-year and 100-year ARI floods in the present-day and with projected climate change. In the downstream

[3] MIKE FLOOD (mikepoweredbydhi.com).

Table 1 Primary sector areas affected by flood by water depth levels and 10-year, 20-year, 50-year, and 100-year Average Recurrence Intervals (ARIs) in the present-day, and with projected climate change

Water depth, m	10-year ARI, ha		20-year ARI, ha		50-year ARI, ha		100-year ARI, ha	
	Present-day	Climate change	Present-day	Climate change	Present-day	Climate change	Present-day	Climate change
0.0–0.5	1,610	1,190	1,637	1,198	1,627	1,263	1,685	1,252
0.5–1.0	1,058	1,185	1,067	1,208	1,169	1,236	1,220	1,280
1.0–1.5	504	1,579	690	1,519	638	1,565	683	1,605
1.5–2.0	125	530	198	775	447	921	567	903
2.0–2.5	70	200	84	226	108	349	163	537
≥2.5	46	74	64	100	90	135	113	174
Total area	3,413	4,758	3,740	5,026	4,079	5,469	4,431	5,751

Table 2 The ratio in Earnings Before Interest and Taxes (EBIT) reduction of dairy, sheep and beef and other pasture, fruits and vegetables, and forestry due to production loss and repair costs

Water depth, m	The ratio in EBIT reduction due to production loss				The ratio in EBIT reduction due to repair costs			
	Dairy	Sheep and beef, and other pasture	Fruits and vegetables	Forestry	Dairy	Sheep and beef, and other pasture	Fruits and vegetables	Forestry
0–0.5	0.248	0.085	0	0.180	0.178	0.258	0	0
0.5–1.0	0.512	0.375	0.224	0.180	0.414	0.619	0	0
1.0–1.5	1.092	0.838	2.462	0.180	0.717	1.340	–0.819	0
1.5–2.0	1.398	1.075	2.686	0.180	0.812	1.340	–0.789	0
> 2.0	1.471	1.053	2.686	0.180	1.003	1.598	–0.758	0

portion of the catchment, both flood extent and depth are projected to increase with climate change.

2.2.2 Financial Costs of Flood

We used information from secondary sources to consider production losses and repair costs of land uses under different flood depths (MPI 2015; Wyatt et al. 2014; MacIntosh 2004). Production losses and repair costs under different flood depths are distributed according to the spatial information of agricultural land area and use categories and farm boundaries (see Section 2.2.1 for details). We assumed six water depth levels in half-metre intervals to be able to distinguish primary sector production losses and repair costs at different flood levels (Table 2). As we aimed to analyse the annual impacts of floods and because of insufficient data on the probability of seasonal floods, we assumed the average annual flood losses for both summer and winter.

For flood damage costs, we used a relative (ratio) change in Earnings Before Interest and Tax (EBIT) due to production losses and repair costs incurred from flooding. We considered that the ratio of production losses and repair costs under six water depth levels for sheep and beef intensive finishing, sheep and beef hill country, and other pastures are the same. The ratio of production losses and repair costs to EBIT across dairy systems also does not differ. We assumed that production losses of forestry do not change with water depth levels and that there are no repair costs for this land use. A negative repair cost for fruits and vegetables indicates the saving in harvest costs because of a flood. At low flood water depth levels, there are no costs for fruits and vegetables as it is assumed the plants are under low stress (Wyatt et al. 2014).

Farm management practices and environmental outputs at farms were assumed not to change with different flood water depth levels, as farmers would not be adjusting their management practices to account for flood risk.

2.3 Economic Land Use Model

Once the areas prone to flooding and the farm-level financial costs of flooding were identified with RiskScape (see Section 2.2), we used the New Zealand Forest and Agriculture Regional Model (NZFARM) to assess the impacts of production losses and repair costs of floods under climate change on land-use change at each farm; and then to assess the subsequent change in net revenues and environmental outputs. A mathematical representation of the NZFARM is given in Appendix 3.

NZFARM is an agri-environmental, nonlinear economic mathematical programming model that accounts for all major farming and land use types in New Zealand (Daigneault et al. 2018). NZFARM changes land uses at each farm to maximise the net revenue from agricultural and forestry activities subject to all farms' land area in the catchment. It is a static model and does not account for dynamic impacts of flooding due to insufficient information on economic and environmental impacts of ARI floods. The model accounts for different flood depth levels.

Performance indicators tracked within NZFARM include economic (e.g. production and EBIT) and environmental (e.g. GHG emissions, carbon sequestration, nutrient leaching, sediment, and water yield) indicators. We considered the direct tangible and direct intangible impacts of floods. Direct tangible flood impacts include changes in farm economic performance. Direct intangible impacts are impacts of a flood on environmental outputs including GHG emissions, carbon sequestration, nutrient leaching, sediment, and water yield. We assumed that floods impact farms' environmental outputs through land-use change at farms, because we did not have sufficient data to calculate the direct flood impact on environmental outputs.

We also assumed farm enterprises can change their land use and do not change their management practices (e.g. change fertiliser and stocking rates) as an adaptation measure to flooding (e.g. Nguyen et al. 2022). We also assumed that forestry plantations can move to moderate, high and very high suitable lands for forestry production, while farms with more than 50% lands of unsuitable, very low and low suitability lands for forestry cannot plant forestry, except farms that already have forestry (for the description of land suitability for forestry, see *Land Atlas of New Zealand*).[4]

We assumed that unfarmed land does not have any GHG emissions and nutrient leaching as it is not involved in any agricultural activities. For annual net revenues for forestry, we included its annuity, which consists of returns from timber production and Emissions Trading Scheme (ETS) payments for carbon sequestration. Among environmental outputs, only the carbon dioxide sequestered by forestry has a financial value; its value is \$68/tCO_2e (the CO_2e price in ETS at the time of the analysis).

We validated the performance of NZFARM model by comparing the land-use areas of the baseline scenario against the observed values in the catchment (e.g. Daigneault et al. 2018; Djanibekov et al. 2013). The modelled land-use areas in the baseline are the same as their observed values (see Table 9 in Appendix 1, and Table 10 in Appendix 4). This is due to that the current information on land-use areas is built considering flood events. In addition, our decision variable is only the land-use area allocation and we do not consider farm management practices (e.g. change fertiliser and stocking rates), which further reduces the number of variables in the model and the deviation between the baseline results and observed situation.

[4] https://ourenvironment.scinfo.org.nz/maps-and-tools/app/Land%20Suitability/lri_prod_for_suitability.

2.4 Monetary Valuation of Environmental Outputs

The estimates of environmental outputs produced by the NZFARM model are land-use-related GHG emissions, carbon sequestration, nitrogen and phosphorous leaching, sediments, and water yield, which are associated with various benefits or costs. The value of carbon sequestered by forestry is already factored into the EBIT for forestry. To monetise changes in the biological GHG emissions between the baseline and the climate change scenarios related to land-use change, we used the ETS CO_2e price of $\$68/tCO_2e$.

Direct values of water yield were estimated using the cost of irrigation water in New Zealand (Rutledge et al. 2010), which is NZ$1.43/$m^3$ (the 2004 value inflated to 2021; MAF 2004). There are studies in other parts of the world that looked at the indirect value of water yield for maintaining ecosystems (Grossmann 2011; Crase and Gillespie 2008); however, they are specific to particular water bodies, making the use of benefits transfer problematic given the differences to the Awanui catchment.

The direct impact of erosion is associated with agricultural productivity, drinking water, flood damage, and sedimentation of waterways. Soliman and Walsh (2022) estimate the cost of erosion to agriculture in New Zealand ranges between NZ$0.03 and NZ$4.10/tonne of sediment. Barry et al. (2014) estimated the flood damage cost of NZ$0.90/tonne of sedimentation and the avoided water treatment costs of the urban water supply of NZ$5.60/tonne.

The indirect impact of erosion is associated with the water quality of waterways. Water quality can be valued using the benefits transfer method based on existing New Zealand water quality studies. Walsh et al. (2021) conducted a choice experiment to evaluate region-specific willingness to pay (WTP) for changes in nutrients, water clarity, and *E. coli* levels. We rely on approach of Walsh et al. (2021)as it is designed for use in policy analysis and contains attribute levels that can be quantified as changes in water clarity. The change in clarity due to a change in sediment load at a stream segment level for this analysis was calculated using an approach developed by Hicks et al. (2019) following Neverman et al. (2019). The changes in clarity of the stream segments were then weighted by the length of each stream segment and added together to get the reach-weighted catchment average. We assumed that climate-induced changes in floods have a similar impact on changes in sediment load and average clarity in all catchments in the region. We estimated the value of improved clarity to the households of the Awanui catchment using the number of households in the catchments and a WTP of NZ$131 per 10 cm of clarity improvement.

2.5 Scenarios

The NZFARM model analyses the impact of four climate change scenarios and compares them with baseline scenarios. The results of these scenarios are then used to value environmental outputs. We simulated three versions of the baseline, all without climate change projections: 10-year ARI, 100-year ARI, and All ARIs. The three baselines enabled us to consider the impacts of each set of ARIs' on the primary sector production losses and repair costs. The All ARI baseline includes expected annual 10-year, 20-year, 50-year, and 100-year ARIs of floods. The 10-year baseline only includes the 10-year ARI flood, and similarly, the 100-year ARI baseline only includes the 100-year ARI floods. The baseline scenarios consider year 2019, because they use land-use areas as of 2019. For the baseline scenarios, the current land use was calibrated to the extent and severity of present-day

Table 3 Modelled climate change scenarios

Scenarios	Description
10 ARI	Impacts of a 10-year ARI flood event.
100 ARI	Impacts of a 100-year ARI flood event.
All ARI	Impacts of 10-year, 20-year, 50-year and 100-year ARI flood events.
All ARI and GHG price	Impacts of 10, 20, 50 and 100-year ARI flood events. Agricultural biological greenhouse gas emissions are priced at \$68/tCO_2e with farmer point of obligation, where farmers pay the price of 5% of their biological emissions.

floods and losses due to floods (for description of calibration see Appendix 3). We did not explicitly consider any agri-environmental policies for the baseline scenario, except ETS for forestry.

The climate change scenarios were based on different flood frequencies that occur with a 2.1°C increase in temperature (Table 3). We also included one scenario where farmers face a GHG price for the GHGs they emit from agricultural activities. The four climate change scenarios modelled in NZFARM included:

1) *10 ARI* - considered the impact of only 10-year ARI flooding with climate change. We estimated the expected annual costs of a 10-year ARI flood by dividing production losses and repair costs of this flood by 10.
2) *100 ARI* - considered the impact of only 100-year ARI flooding with climate change. A 100-year ARI flood event has a 1% probability that a flood will occur in any single year.
3) *All ARI* - included all 10-year, 20-year, 50-year, and 100-year ARI floods with projected climate change, because farmers will be making decisions that consider all the possible flood events and the probability they will occur. To annualise the total economic costs of these flood events we first divided the total production losses and repair costs of each ARI flood event by the years of the recurrence interval for that flood, and then summed these cost.
4) *All ARI and GHG price* - included all ARI floods and farmers are the point of obligation for agricultural GHG emissions.[5] Farmers receive 95% free allocation for their GHG emissions, meaning they face a direct price on 5% of their biological GHG emissions (i.e. at a GHG price of \$68/tCO_2e, farmers pay \$3.4/tCO_2e for their biological GHG emissions). To capture the impacts of floods under projected climate change, we assumed that the percentage of free allocation does not change in the climate change scenarios.

2.6 Data Sources

Agricultural and forestry land area and use categories within the Awanui catchment came from AgriBase (AssureQuality 2020), Land-Use and Carbon Analysis System (LUCAS) and the New Zealand Land Cover Database version 5.0[6] (Newsome et al. 2018; MWLR

[5] According to climate change obligations for New Zealand's primary sector that are planned to start in 2025, farmers will receive obligations to reduce GHG emissions from their farms.

[6] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/.

2016). Agricultural and forestry land area includes information for each farm and is based on year 2019. The Awanui catchment boundary was represented by vector polygons from the River Environment Classification v2.0 (REC2) (NIWA 2022). We used the *Land Atlas of New Zealand*[7] to make assumptions on the suitability of different areas for plantation forestry. We assessed the possible impact of floods on Māori farmland using spatial information on Māori land locations from Māori Land Data Service.[8]

We used information from the DairyNZ Economic Group (2017) on net revenues, GHG emissions, and nitrogen and phosphorous losses for dairy systems across New Zealand. Based on the DairyNZ Eonomic Group (2017), we classified dairy systems into systems 2 and 3. The sheep and beef data were based on the sheep and beef farm budgets of Beef + Lamb New Zealand (2017). Sheep and beef farms were classified into 'sheep and beef hill country' and 'sheep and beef intensive finishing' classes (Beef + Lamb New Zealand 2017). However, information from DairyNZ Economic Group (2017) and Beef + Lamb New Zealand (2017) does not include information on ethnicity, socio-demographic, non-agricultural incomes and other characteristics of farms. Using the New Zealand GHG inventory methodology (MfE 2017), we estimated the GHG emissions for the sheep and beef farms and other pasture. We used nutrient budgets for sheep and beef from Daigneault et al. (2018). The base year for EBIT and GHG emissions is 2017.

We used the timber outputs and carbon sequestered by *Pinus radiata* plantations from CenW, a forest-growth model (Kirschbaum 1999). The horticultural farm budgets and GHG emissions came from Horticulture New Zealand (Djanibekov et al. 2018). The EBIT and nutrient budget of other pasture were from Daigneault et al. (2018). The unfarmed land use does not have economic and environmental outputs as this land use has no agricultural activities.

Sediment loads were obtained from the New Zealand Empirical Erosion Model (NZeem$^{(R)}$) sediment model, which is calibrated to sediment discharges measured in New Zealand rivers (Dymond et al. 2010). We used the outputs of the WATYIELD model to estimate water yield for land uses (Fahey et al. 2010).

3. Results

3.1 Flood Exposure Area and Damage Costs

The RiskScape results on the present spatial extent and damage costs of floods on the primary sector under current land-use patterns are given in Tables 4 and 5. The results in tables are the inputs for analysing the economic impacts of floods with NZFARM and environmental valuation.

The RiskScape shows that sheep and beef intensive finishing land is most exposed to present-day flooding (Table 4). In present-day, the most area of all land uses are under the lowest flood water depth level of 0–0.5 m (see Fig. S1 in Supporting Information).

If there is no land-use change and the land-use pattern remains as in the present-day, then the total land exposure increases by 29–38% for the flood ARI scenarios with climate change. In comparison to the present-day situation, with climate change the flood water

[7] https://ourenvironment.scinfo.org.nz/maps-and-tools/app/Land%20Suitability/lri_prod_for_suitability.

[8] https://maorilandcourt.govt.nz/your-maori-land/maori-land-data-service/.

Table 4 Land-use area exposure to flooding in present-day and projected climate change situations, ha

Land uses	Total area of land use, ha	Land-use area exposed to flooding							
		10-year ARI		20-year ARI		50-year ARI		100-year ARI	
		Present-day	Climate change	Present-day	Climate change	Present-day	Climate change	Present-day	Climate change
Dairy system 2	1,560	113	120	119	124	124	129	128	132
Dairy system 3	5,521	1,081	1,680	1,179	1,750	1,278	1,854	1,379	1,926
Forestry	1,799	13	16	14	17	16	19	17	21
Fruits	70	1	2	2	2	2	3	2	3
Other pasture	43	5	8	5	8	6	11	7	11
Sheep and beef hill country	12,822	266	320	289	342	318	369	344	391
Sheep and beef intensive finishing	12,129	1,861	2,350	2,045	2,505	2,228	2,789	2,425	2,960
Vegetables	197	29	142	36	142	45	143	53	143

Table 5 Expected annual flood damage costs (including production losses and repair costs) in the present-day and projected climate change situations, % change from the observed net revenues

Land uses	10-year ARI		20-year ARI		50-year ARI		100-year ARI	
	Present-day	Climate change	Present-day	Climate change	Present-day	Climate change	Present-day	Climate change
Dairy system 2	0.9	1.0	0.5	0.6	0.2	0.2	0.1	0.1
Dairy system 3	1.5	4.3	0.9	2.3	0.4	1.0	0.2	0.5
Forestry	0.01	0.02	0.01	0.01	0.003	0.004	0.002	0.002
Fruits	0.06	0.08	0.04	0.05	0.02	0.02	0.01	0.01
Other pasture	2.3	2.3	0	2.3	0	0	0	0
Sheep and beef hill country	0.3	0.3	0.2	0.2	0.07	0.1	0.04	0.05
Sheep and beef intensive finishing	1.5	2.8	0.9	1.5	0.4	0.7	0.3	0.4
Vegetables	0.07	3.8	0.04	2.0	0.02	0.8	0.01	0.4
Total costs	1.0	2.6	0.6	1.4	0.3	0.6	0.2	0.3

Table 6 Change in land-use area for the climate change scenarios

Land uses	Baseline, ha	Climate change scenarios, % change			
		10 ARI	100 ARI	All ARI	All ARI and GHG price
Dairy system 2	1,560	0	0	0	–0.1
Dairy system 3	5,521	–0.1	0	–0.8	–1.1
Sheep and beef hill country	12,822	–0.1	0	–0.2	–3.3
Sheep and beef intensive finishing	12,129	–1.2	0	–3.0	–7.4
Other pasture	43	–16.5	–1.8	–21.3	–90.7
Forestry	1,799	1.1	0	3.1	4.0
Fruits	70	0	0	4.1	9.2
Vegetables	197	0	0	1.5	3.3
Unfarmed land	344	41.1	0.2	112.4	391.1

Baseline land-use areas are the same across scenarios

depth levels increase and larger areas are exposed to deeper flood water levels (see Fig. S2 in Supporting Information). For example, sheep and beef intensive finishing and dairy system 3 land uses are expected to have the largest area under the flood water depth level of 1–1.5 m.

With the current land-use pattern, dairy system 3 has the highest flood damage costs under both present-day and projected climate change scenarios because it has large areas exposed to flood and large production losses and repair costs from flooding (Table 5). The flood damage costs substantially vary depending on water depth levels and ARIs (see Figs. S3 and S5 in Supporting Information). For instance, the largest production losses and repair costs are for dairy system 3 that are affected by 0.5–1 m flood water depth level and 10-year ARI. The lower is ARI flood the larger is the probability of flood occurrence and thus the larger are possible flood damage costs.

With climate change projections, the total costs for land uses can be 100% and 160% larger than in the present-day considering that the current land-use pattern remains. The largest amount of production losses and repair costs under projected climate change occur with flood water depth levels of 1–1.5 m followed by 1.5–2 m (see Figs. S4 and S6 in Supporting Information).

3.2 Land-Use Change

We used calculations done by the RiskScape in Section 3.1 in the NZFARM to simulate four climate change scenarios. Our results show that with projected climate change there is a change in land use to reduce the negative impacts of new flood patterns (Table 6). When considering a 100-year ARI flood under climate change (100 ARI scenario), the areas of land use change slightly from the baseline. Although large areas of agricultural and forestry land uses are exposed to a 100-year ARI flood (Table 1), this has a small impact on land-use change due to its small probability of occurrence, i.e. probability of occurrence once every 100 years.

Lower ARIs have a higher probability of occurrence and thus have greater impacts on land-use change. For example, more land-use change occurs with a 10-year ARI flood than with a 100-year ARI flood with projected climate change due to the probability of occurrence once every 10 years with 10-year ARI against the probability of occurrence once every 100 years with 100-year ARI. With a 10-year ARI flood (10 ARI scenario), the areas of pastoral land use reduce, as they are more exposed to flood and experience higher flood damage costs than other land uses (see Figs. S2, S4 and S6 in Supporting Information). Pastoral land mostly shifts to unfarmed land, because unfarmed land does not incur economic losses from flooding. Although forestry can still generate EBIT, most of the shifted pastoral land area cannot be planted for forestry due to its low suitability for forestry.

Combining all the flood events we modelled, i.e. 10-year, 20-year, 50-year, and 100-year ARI floods (All ARI scenarios), results in substantial land-use change. The largest decrease in area is seen in sheep and beef intensive finishing (3% reduction, 364 ha); followed by dairy system 3 (0.8% reduction, 44 ha), which has the largest areas exposed to flooding with high flood damage costs. There is no change in the area of dairy system 2 from the baseline as it is less exposed to flood. Pastoral land mainly moves to unfarmed land, which increases by 112.4% (387 ha). The areas of forestry and horticultural crops also increase slightly. Even though floods reduce the EBITs of forestry and horticultural crops, they can still generate higher EBIT in some locations where pastoral farms are being affected by flooding. If we look at individual farms, none of the farms in the catchment have entirely changed their land use (farm information not shown due to confidentiality). Of 465 farms, 102 have partially changed their land-use areas. Four sheep and beef intensive finishing farms have converted about 92% of their area to unfarmed land, forestry and/or horticulture.

A policy pricing agricultural GHG emissions with 95% free allocation (All ARI and GHG price scenarios) results in the largest land-use change with projected climate change. About 379 farms out of 465 farms have some change in their land-use area. Both flood damage costs and a price on biological GHG emissions increase costs for agricultural land uses, particularly pastoral farms that have the highest biological GHG emissions and are in flood-exposed areas. Like other climate change scenarios, only the area of pastoral production reduces in this scenario. About 1,345 ha of pastoral farms are no longer farmed, which increases the unfarmed area by 391%. Some pastoral land also moved to forestry (72 ha), fruits (6 ha) and vegetables (7 ha), because of their lower flood damage and GHG emission costs in flooded areas. The biggest reduction in the area was for sheep and beef intensive finishing and hill country followed by dairy system 3. Most sheep and beef intensive finishing and hill country farms (360 farms out of 362) have partially changed land use, with a change to unfarmed land, forestry and/or horticulture.

The farms identified as under Māori ownership in the Māori Land Data Service farms did not appear to be affected by flooding, and no land-use change was noted for Māori farms.

Figure 3 shows the expected locations of land-use change for dairy system 3, sheep and beef intensive finishing, forestry, and unfarmed land in the All ARI scenario. The maps show indicative locations. Land-use change is modelled as mostly occurring near the mouth of the catchment where flooding has higher water depths. Most of the dairy system 3 and sheep and beef intensive land-uses convert to unfarmed land, with conversion to forestry in a few locations.

3.3 Net Revenue Change

Even though the modelling shows farmers change their land uses to reduce the costs of flooding, floods still decrease the total catchment net revenue of the primary sector (Table 7). For the 100-year ARI flood, which is the flood event with the lowest probability

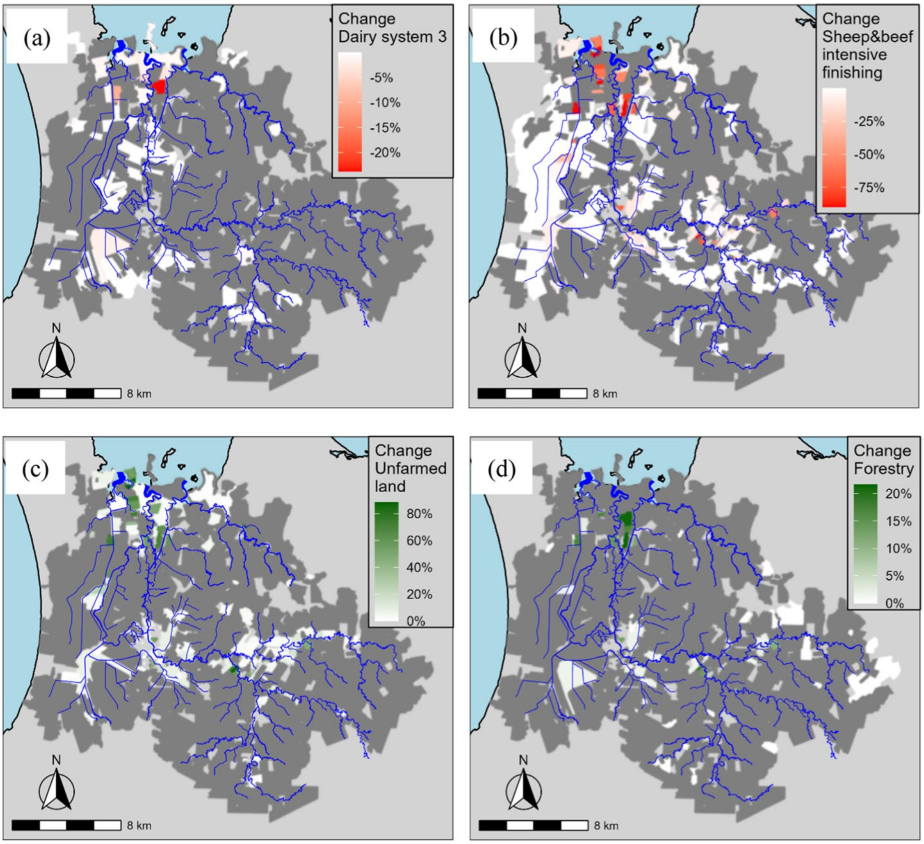

Fig. 3 Locations of percentage change of each land-use polygon in the Awanui catchment between baseline and All ARI climate change scenarios for the most affected land uses: **a** Dairy system 3; **b** Sheep and beef intensive finishing; **c** Foresty; **d** Unfarmed land

of occurrence among simulated floods and has the lowest land-use change, the primary sector's total net revenue was reduced by 0.2%. The more frequent 10-year ARI flooding has a larger decrease in net revenues than a 100-year ARI flood. In this scenario, the biggest impacts in absolute terms are on dairy system 3 and sheep and beef intensive finishing, which have reductions in net revenues of NZ$ 295,400 (2.9%) and NZ$ 108,350 (2.3%), respectively.

The All ARI scenario further reduced net revenues from the primary sector (decrease by 3.1%). In absolute terms, the largest decreases were for dairy system 3 (decreased by 5.7%), followed by sheep and beef intensive finishing farm (decreased by 4.6%). Dairy system 3 has the largest decrease in net revenue because of the vast area of this farm type that floods and the high flood damage costs (see Figs. S2, S4 and S6 in Supporting Information). Vegetable net revenue decreased by 5.7%, although its area increased (see Section 3.2). The decrease in the vegetable net revenue is because of the size of the area exposed to flooding under projected climate change, and the increase in the vegetable area does not offset the

Table 7 Change in primary sector net revenues for the climate change scenarios

Land uses	All ARI			10-year ARI		100-year ARI	
	Baseline, NZ$1,000	All ARI scenario, % change	All ARI and GHG price scenario, % change	Baseline, NZ$ 1,000	Climate change scenario, % change	Baseline, NZ$ 1,000	Climate change scenario, % change
Dairy system 2	1,759	–0.2	–2.6	1,775	–0.1	1,789	–0.01
Dairy system 3	10,025	–5.7	–7.2	10,187	–2.9	10,319	–0.3
Sheep and beef hill country	4,384	–0.3	–7.0	4,395	–0.1	4,406	–0.01
Sheep and beef intensive finishing	4,632	–4.6	–12.6	4,711	–2.3	4,765	–0.1
Other pasture	0.041	–19.6	–228.7	0.042	–15.3	0.042	–1.8
Forestry	3,001	3.0	3.9	3,001	1.1	3,001	–0.0004
Fruits	362	3.3	7.4	362	–0.01	362	–0.002
Vegetables	1,836	–5.7	–4.3	1,837	–3.8	1,838	–0.4
Total net revenue	25,999	–3.1	–6.2	26,268	–1.7	26,488	–0.2

Three different baseline net revenues are modelled (i.e. in 10-year, 100-year, and All ARI baseline scenarios) because in each of the baselines, we consider different ARI flood exposed areas and thus, they have different flood production losses and repair costs for the primary sector damage costs of the vegetable area that is exposed to flooding. Vegetables remain in these flood-exposed areas as they are still more profitable than other land uses. The net revenue for forestry and fruit increased in this scenario because the areas where these land uses are located are less affected by the flood, and they have lower damage costs and higher EBIT (in the case of fruits) than pastoral land uses.

Among all scenarios, the All ARI with GHG price scenario has the biggest impact on the catchment net revenue for the primary sector. The reduction in net revenue is twice the size of the All ARI scenario. As with other scenarios, dairy system 3 (decrease of 7.2%) and sheep and beef intensive finishing (decrease of 12.6%) have the largest decrease in net revenue in the All ARI and GHG price scenario. While the reduction in net revenue for other pasture is 228.7%, in absolute terms, this reduction is small in contrast to the reduction in net revenue for dairy and sheep and beef farms.

3.4 Environmental Outputs and Monetary Values

Land-use change caused by floods affects the environmental outputs of land uses indirectly (Table 8). We consider the change in environmental outputs due to land-use change only because of insufficient data on flood impacts on the environmental conditions in the catchment.

Floods indirectly reduce GHG emissions from agriculture as a result of a reduction in the area of pastoral farms (see Section 3.2). The reduction in emissions can generate benefits at NZ$144,253/year for the All ARI scenario and NZ$421,095/year for the All ARI and GHG price scenario. Carbon sequestration increases, but the increase in benefits from the baseline is lower than when pricing GHG emission reductions. Note that carbon sequestration benefits are included in the EBIT for forestry, while other environmental outputs are valued using a non-market valuation approach.

The modelled land-use change results in water yield reduction. Water yield reduces as a result of an increase in the area of more water-intensive land uses, including forestry and horticulture. Most of the changes occur in the lower part of the Awanui River, below the town of Kaitaia. The monetary values of reduced water yield for the catchment for the scenario with the greatest land-use change are NZ$242,439/year lower than in the baseline scenario.

Sediment load reduces in each climate change scenario. We do not estimate the direct value of changes in sediment load for several reasons. The sediment reduction takes place only on farms that underwent land-use change from pasture or other agricultural uses to forestry or to unfarmed land. Therefore, the impact of erosion on agricultural production is not relevant. Similarly, water treatment costs are not relevant for this analysis as most of the changes in sediment load occur downstream of Kaitaia, and there is no dredging needed, given there is no reservoir downstream. Therefore, we estimate the indirect value of sediment load through its impact on water quality.

The average water clarity changes presented in Table 8 are small (0.13 cm for the All ARI and GHG price scenario). This is because very few stream segments in the catchment had changed (reduced) sediment load. The monetary value of improved clarity is NZ$2,063/year for the whole catchment in the All ARI scenario and NZ$5,168 for the All ARI and GHG price scenario. Finally, we did not estimate the monetary values of the

Table 8 Change in environmental outputs and their monetary values

Environmental outputs	Units	Baseline	10 ARI,		100 ARI		All ARI		All ARI and GHG price	
		Value	Change	Change, NZ$	Change	Change, NZ$	Change	Change, NZ$	Change	Change, NZ$
Greenhouse gas emissions	tCO_2e/year	152,548	–746	50,702	–3	213	–2,121	144,253	–6,340	431,095
Carbon sequestration	tCO_2e/year	21,956	243	16,500	0	0	677	46,021	895	60,843
Water yield	1,000 m^3/year	302,791	–38	–54,730	0	0	–118	–168,446	–169	–242,439
Sediment load	t/year	253,569	–26	n.a.	0	n.a.	–68	n.a.	–171	n.a.
Average clarity	cm	124.77	0.02	794	0	0	0.05	2,063	0.13	5,168
Nitrogen	kg/year	307,573	–929	n.a.	–8	n.a.	–2,796	n.a.	–9,072	n.a.
Phosphorous	kg/year	47,949	–73	n.a.	0	n.a.	–384	n.a.	–798	n.a.
Total				13,266		213		23,891		254,667

n.a. means monetary values are not estimated. Carbon sequestration benefits are included as market values in the Earnings Before Interest and Taxes (EBIT) for forestry changes in N and P because we were unable to convert changes in N or P to water quality in the catchment and because of their negligibly small values.

The monetary values of changes in environmental outputs other than GHG emissions are small compared to reductions in the total net revenue for the Awanui catchment resulting from climate change-induced flooding. For the All ARI and GHG price scenario, the change from the baseline in total net revenue is –$1,611,000, the change in the value of carbon emissions is $431,095, and the change in the estimated values of other environmental outputs is –$176,428.

Figure S7 in Supporting Information provide information on environmental outputs by land uses.

4. Discussion and Conclusions

4.1 Flood Impacts

Climate change has a signifant adverse costs to the societe (Newman and Noy 2023). It is expected that only in 10 countries the increase in flooding due to climate change could cause more than US$2 trillion in losses by 2050 (Aquanomics 2022). We show that even with existing flood management schemes, flood exposure and flood damage costs increase with projected climate change in the Awanui catchment, New Zealand. The flood damage costs are 2–2.5 times larger with projected climate change than in the present-day. The flooded area increases for the single event scenarios (i.e. 100-year ARI, and 10-year ARI), and for scenarios that consider all possible flood events (i.e. All ARI, and All ARI and GHG price).

The extent and impacts of future flood damage are highest when all the flood events are considered (i.e. All ARI, and All ARI and GHG price scenarios) and focused on certain locations. Climate change is projected to increase water depth levels for areas that are currently mostly sheep and beef intensive finishing, dairy system 3 and other pasture farms. As a result, these land uses bear the highest flood damage costs. In New Zealand, more high-value land uses, such as dairy, have been highly exposed to flooding over the last two decades (Craig et al. 2021). If the current land-use pattern continues with projected climate change, the most profitable pastoral farms that make a substantial contribution to GDP (The Treasury New Zealand 2022) will be the most affected by floods, which will increase the economic risks faced by the agricultural sector.

Floods can have disproportionate impact to population groups. AON (2022) reports that flood risk falls unequally on Māori and Asian New Zealanders, as well as on low income households and deprived areas. We show that Māori farms were not affected by flooding in the catchment; however, we cannot identify the impact on other ethnicities and income groups. Besides, residential buildings and other properties under Māori ownership might be impacted by flooding, which were not addressed in this study.

Flooding can also have indirect and intangible impacts (Merz et al. 2010). For instance, Nga et al. (2018) showed that 6% of agricultural production is at flood risk annually in Central Vietnam, where 62% of flood damage costs are related to indirect and intangible costs, including clean-up, recovery, soil and water remediation, and business interruption costs. Carrera et al. (2015) combined spatial analysis of flood damage with an economy-wide model to assess the direct and indirect impacts of flooding in Italy. They showed that not all effects of floods are negative, there may also be indirect positive effects in some locations of the country. In our study, land-use change from pastoral farms to other land uses in response to climate change-induced flooding results in a reduction of GHG emissions, nitrogen and phosphorous leaching, and sediment outputs, particularly when the largest environmental change is simulated with all flood events considered (i.e. All ARI, and All ARI and GHG price scenarios). The increase in forestry area in the 10 ARI, All ARI, and All ARI and GHG price scenarios also increases the carbon sequestered in the catchment. However, these environmental benefits are small, and their monetised values do not cover the direct economic losses of flooding. In addition, water yield reduces as a result of land-use change.

4.2 Flood Adaptation

Farmers possess a vast experience dealing with extreme weather events (e.g. Griffin et al. 2023; Ntim-Amo et al. 2022). Land-use change along with crop diversification, and leaving agricultural fields idle are one of the main adaptation measures of farmers to reduce flood damage costs (Thennakoon et al. 2020). For example, in the Vietnamese Mekong Delta, land-use change has reduced the flooding of rice fields between 2000 and 2020 (Vu et al. 2022). Land-use change is also modelled to be a viable option to reduce the flood damage costs in the Netherlands (Brouwer and van Ek 2004). In New Zealand, flood events have been affecting farmers' practices and farmers have been selecting adaptation pathways including land-use change (Griffin et al. 2023).

Our modelled scenarios that consider all possible flood events that farmers might face with climate change (all ARI flood events and ARI floods with GHG price), result in the largest land-use change because these scenarios have the highest flood damage costs. Large areas of sheep and beef intensive finishing, sheep and beef hill country, and dairy system 3 convert to other land uses. These pastoral land uses are the most flood-exposed land uses and have the largest flood damage costs. In areas where flood damage costs are high, farmers may prefer to leave land idle rather than actively farm those areas. Some flood-exposed areas of pastoral farms are also converted to forestry and horticultural crops. Forestry can reduce the negative impacts of flooding, while forest loss can increase the negative impacts (Villarreal-Rosas et al. 2022). The flood adaptation measures including the land-use change affect the economic, social (e.g. employment) and environmental performance of farms (Blaschke et al. 2008). The flood adatation behaviour of farmers is dependent on local knowledge, place-based experience, values and perceptions of fairnes (Griffin et al. 2023; Paulik et al. 2021). At the same time, trade-offs need to be considered when farmers implement flood adaptation strategies, because they can also increase the intensity and frequency of floods by increasing surface runoff (Villarreal-Rosas et al. 2022; Tao et al. 2011).

It is expected that climate policies can alleviate the impacts of climate change and reduce flood damage costs (IPCC 2023). Our study shows that introducing climate change mitigation policy, such as pricing of biological GHG emissions, achieves the largest reduction in agricultural GHG emissions and increase in forestry carbon sequestration. However, pricing of biological GHG emissions alongside the flood damage costs results in the biggest reduction in most economic outputs for the primary sector, especially for pastoral farms, because they are the most flood-exposed land uses and have high biological GHG emissions. The economic impact of pricing biological GHG emissions together with more damaging flood events is double the cost of climate-induced flooding costs alone. The implementation of other agri-environmental policies is likely to further decrease farmers' net revenues (Daigneault et al. 2018). Hence, it is vital to consider farms that are at the most risk of future flooding and the possible negative effects of these policies on farms, during climate policy development. To enhance the resilience of the primary sector, upcoming policy initiatives from the government and industry could focus on identifying land uses that are more vulnerable to flooding and facilitate their transition to less flood-prone areas. This strategy would not only minimise the economic impacts associated with such land uses but also promote greater resilience in the agricultural industry.

4.3 Integrated Analysis and Further Research

The high expected flood hazard suggests a need for the development of methodologies that can be used to assess damage costs as a basis for decision-making on climate change adaptation (Halsnæs et al. 2023). Our study contributes methodologically to the understanding of flood damage effects and land use adaptation responses by simultaneously considering different flood parameters and impacts on the primary sector, and adaptation responses by farmers to flooding using an integrated approach. We show how flooding leads to production losses and repair costs (direct tangible impacts) for the primary sector, and changes in the environmental outputs (direct intangible impacts) from farms.

However, our study does not capture all types of impacts of flooding. Having information on inundation duration, seasonality and flow velocity of flooding can lead that the integrated approach produces more detailed results on flood damage costs with dynamic impacts, and that some land uses (e.g. forestry and horticulture) might become ineffective adaptation options. In addition, increased frequency and severity of flooding with climate change will also have wider impacts (Carrera et al. 2015). For instance, agricultural employment will reduce if farmers shift away from farming their land (Nguyen et al. 2022). Floods usually also have lagged effects. For example, negative impacts on people's well-being and some components of the environment might be felt for some time after the flood event. Floods may also spread viruses, bacteria and other microbial contaminants that can affect the health of the population and livestock located close to flood-exposed areas (Mahmood et al. 2017). The environmental outputs in our model are also changing based on land-use change and are not responsive to inundation levels. In addition, floods can have disproportionate impacts on different population groups, depending on their ethnicities and income levels (AON 2022). Including these additional flood impacts in the analysis requires additional biophysical (e.g. spatial contaminant movement), environmental (e.g. sediment discharge) and economic modelling and data (e.g. economy-wide and dynamic impacts on population groups).

Appendix 1

Table 9 Observed land-use area, Earnings Before Interest and Taxes (EBIT), net revenues and environmental outputs in the Awanui catchment

Land uses	Land-use area, ha	EBIT, NZ $ /ha/year	Net revenue, NZ$1,000/year	Greenhouse gas emissions and sequestration, tCO_2e/year	Nitrogen leaching, kgN/year	Phosphorous loss, kgP/year	Sediment load, t sediment/year	Water yield, 1,000 m^3/year,
Dairy system 2	1,560	1,148	1,791	12,213	42,113	5,147	15,283	14,182
Dairy system 3	5,521	1,873	10,344	35,707	93,864	34,233	7,237	41,993
Sheep and beef hill country	12,822	344	4,408	48,319	96,075	4,885	197,525	136,256
Sheep and beef intensive finishing	12,129	394	4,784	56,075	64,406	3,275	27,047	92,899
Other pasture	43	1	0.043	179	452	18	173	333
Forestry	1,799	1,668	3,001	–21,956	3,598	360	4,924	13,250
Fruits	70	5,160	362	3	421	7	49	424
Vegetables	197	9,356	1,839	53	6,642	20	133	982
Unfarmed land	344	0	0	n.a.	n.a.	n.a.	1,199	2,472
Total	34,485	0.77	26,529	130,593	307,571	47,945	253,570	300,319

n.a. means data do not exist for unfarmed land. Here net revenues do not explicitly account for the costs of floods with Average Recurrence Intervals (ARI). The total EBIT of land uses represents the average EBIT per hectare of all land uses

Appendix 2

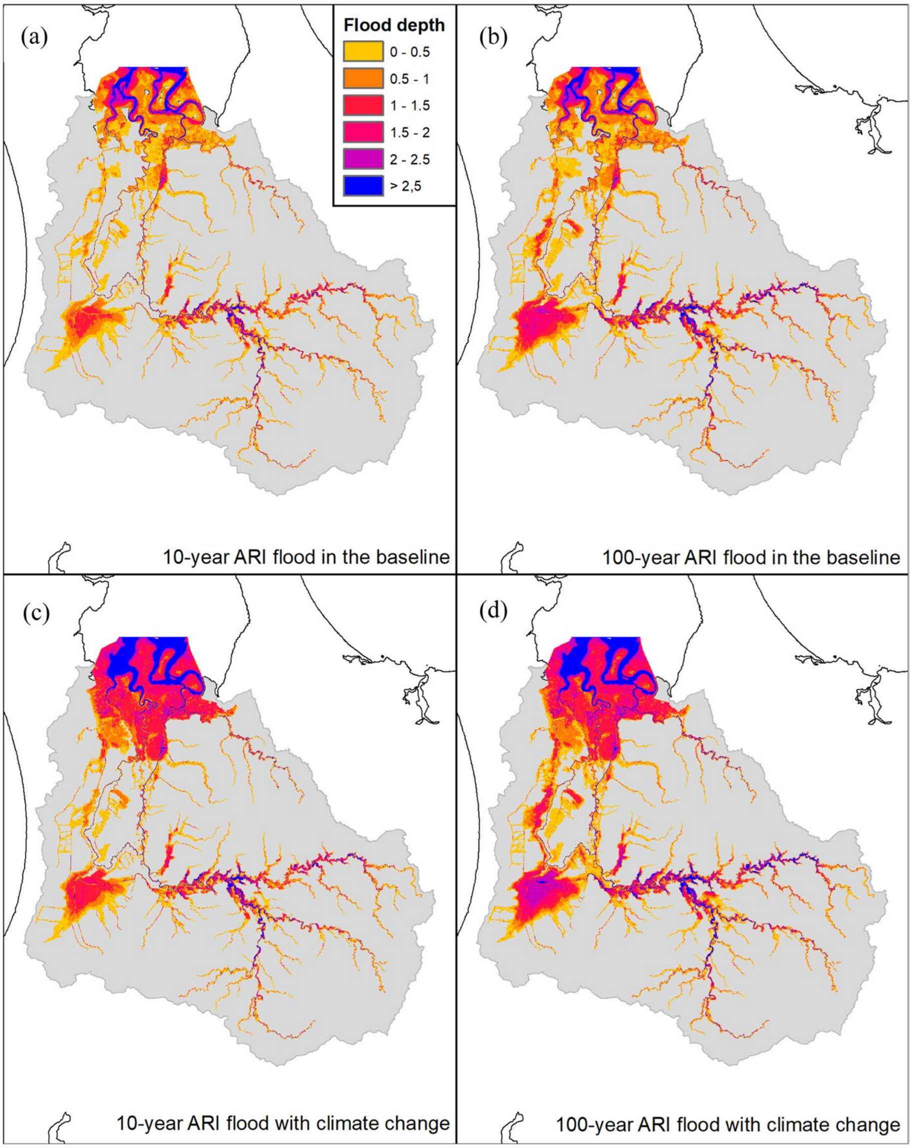

Fig. 4 Extent and depth of floods. Present-day (baseline) for **a** 10-year ARI; **b** 100-year ARI. With projected climate change for **c** 10-year ARI; **d** 100-year ARI

Appendix 3: Mathematical representation of NZFARM

Mathematical equations

The objective function of New Zealand Forest and Agriculture Regional Model (NZFARM) is to determine the maximum summed net revenues from agricultural and forestry activities from all farms in the Awanui catchment under ARI floods, subject to the area constraints of each farm and primary sector production. NZFARM identifies optimal land-use area in each farm that will lead to the maximum net revenues in each simulated scenario. In more detail, the mathematical representation of the objective function is:

$$MaxNR = \sum_{f,l,e} \left\{ b_{f,l,e} X_{f,l,e} - b_{f,l,e} p_{f,l,e,w} s_{f,l,w} X_{f,l,e} - b_{f,l,e} r_{f,l,e,w} s_{f,l,w} X_{f,l,e} + \tau \, env_{f,l,e,o} X_{f,l,e} - \varphi \, env_{f,l,e,g} X_{f,l,e} \right\} \quad (1)$$

where *NR* is the maximum level of net returns from all land uses in Awanui catchment, *b* is the earnings before interest and tax (EBIT) of land uses, *X* is the farm-based land use, *p* is the ratio to EBIT of production loss of land uses from flood, *s* is the share of flooded area depending on ARI, *r* is the ratio to EBIT of repair loss of land uses from flood, τ is the Emissions Trading Scheme (ETS) payment for carbon sequestration in forestry, φ is the price on agricultural GHG emissions with 95% free allocation, *env* is the environmental outputs. Parameter *s* considers the annual expected value of the share of flooded area, i.e. area of 100-year ARI has 1 chance of occurrence in 100 and thus its area is divided by 100. In All ARI and All ARI and GHG Price scenarios, the terms related to production and repair losses of flood include all four simulated ARI's and their respective damage costs. The costs related to pricing of agricultural GHG emissions with 95% free allocation (φ) is included in the scenario considering all ARIs and pricing of GHG emissions. Summing EBIT across all farms (f) in the catchment, land use covers (l) such as pasture, forestry, horticulture and other, and land use types (e) such as dairy, sheep and beef, 'other pasture', fruit, vegetables, forestry and unfarmed land yields the total net revenue for Awanui.

The commodity prices were assumed to remain constant. Also, we assume that environmental indicators do not change with flood impacts. In addition, economic and environmental indicators do not change even with the climate change projections over time.

The maximisation of net revenue is affected by the primary sector production amount, and farmland area. The choice variable in the model is an allocation area of land uses, where optimal land-use area is selected to maximise total net revenue in Awanui. Land uses in each farm that are given in NZFARM are constrained by the available land area as in:

$$\sum\nolimits_{l,e} X_{f,l,e} \leq \sum\nolimits_{l,e} d_{f,l,e} \quad (2)$$

where *d* is the available land-use area by land use cover in each farm. In the observed situation, each farm is engaged in a single land use, i.e. dairy farm is involved only in dairy activity. In simulated scenarios, NZFARM selects the optimal land-use pattern at farm level considering the impact of flood, where the model might select several land uses at farm level, e.g. dairy farm plants forestry plantations and has unfarmed land on some areas. Moreover, we assume that forestry can be planted on moderate, high and very high suitable lands for forestry production (for the description of land suitability for forestry, see *Land Atlas of New Zealand*).[9]

The primary sector production is constrained by the product balance equation that specifies production type by land use type. The production constraint is specified as follows:

$$Q_{f,l,e} \leq \alpha^{proc}_{f,l,e} X_{f,l,e} \tag{3}$$

where Q is the primary sector's product output quantity, $\alpha^{proc}_{f,l,e}$ is the output coefficient from land uses that shows the output levels from land uses in each farm.

The model includes a constraint on forestry area allocation:

$$X_{f,l,e} = 0 \tag{4}$$

where e includes forestry on unsuitable, very low and low suitability lands where it is assumed that farms with more than 50% lands of unsuitable, very low and low suitability lands for forestry cannot plant forestry, unless forestry already exists on such farms.

NZFARM also calculates the change in environmental outputs when the land users maximise net revenues. We consider GHG emissions, carbon sequestration, N leaching, P loss, sediment load and water yield as environmental outputs resulting from land uses. The equation for environmental outputs is included into the model as follows:

$$env_{f,l,e,y} X_{f,l,e} = EN_{f,l,e,y} \tag{5}$$

where env is the coefficient of environmental indicators such GHG emissions, carbon sequestration, N leaching, P loss, sediment load and water yield from land uses, EN is the variable of environmental outputs from selected land uses by the model, and y is the set that consist of environmental indicators.

The model variables are subject to non-negativity constraint, where variables area constrained to be greater or equal to zero such that farmers cannot feasibly have the negative area of land and agricultural outputs:

$$X, EN \geq 0 \tag{6}$$

The model is solved using the General Algebraic Modelling System (GAMS).[10]

Model calibration

To calibrate the baseline area results, we use constant elasticity of transformation (CET) functions and their nested forms.

In the model, the main variable is the land-use area for each of the farm ($X_{f,l,e}$). NZFARM considers that farmers have a degree of flexibility to adjust the share of the land use and enterprise their farm-based activities to meet an objective target such as maximum

9 https://ourenvironment.scinfo.org.nz/maps-and-tools/app/Land%20Suitability/lri_prod_for_suitability.

10 https://www.gams.com/

net revenues. Commodity prices and constraints are exogenous variables, and these variables are constant across scenarios.

The model is parametrised where responses to Average Recurrence Intervals are not drastic and assumed to be instantaneous. The optimal distribution of farm type, land use, and agricultural and forestry outputs in farms are determined using a nested framework that is calibrated based on land-use areas in each farm. At the highest levels of the nest, land use is distributed over the NZFARM farms based on the fixed area of various farm enterprise types that generate the maximum net revenues for the Awanui catchment.

NZFARM simulates allocation of land uses at farm through constant elasticity of transformation (CET) functions. The CET function specifies the rate at which enterprises, and outputs produced can be transformed across the array of available options. This approach is well suited to models that impose resource and policy constraints as it allows the representation of a "smooth" transition across production activities while avoiding unrealistic discontinuities and corner solutions in the simulation solutions (de Frahan et al. 2007). At the highest levels of the CET nest, land use is distributed over the zone based on the fixed area of farms. Land cover is then allocated between several enterprises, such as livestock (e.g. dairy or sheep and beef or 'other pasture'), forestry plantation, horticulture (e.g. fruits, vegetables) that will generate the highest net returns for the catchment.

The CET functions are calibrated using the share of total initial (observed) area for each element of the nest and a CET elasticity parameter for the respective farm, land area, farm enterprise, and agricultural output. We do not consider costs from switching from one land use or enterprise activity to another, such as change in infrastructure, learning management practices for new farming, and other costs.

The CET parameters in NZFARM ascend with each level of the nest between land cover and enterprise. This is because farmers have more flexibility to change their enterprise activities than to alter their share of land cover. The elasticities are related to land cover and enterprise. As we do not consider management practices, we did not include elasticities of management practices.

Appendix D

Table 10 Land-use area and environmental outputs in the baseline

Land uses	Land-use area, ha	GHG emissions or sequestration, tCO_2e	Nitrogen leaching, kg	Phosphorous loss, kg	Sediment load, t	Water yield, 1,000 m^3
Dairy system 2	1,560	12,213	42,113	5,147	15,283	14,182
Dairy system 3	5,521	35,707	93,864	34,233	7,237	41,993
Sheep and beef hill country	12,822	48,319	96,075	4,885	197,525	136,256
Sheep and beef intensive finishing	12,129	56,075	64,406	3,275	27,047	92,899
Other pasture	43	179	452	18	173	333
Forestry	1,799	–21,956	3,598	360	4,924	13,250
Fruits	70	3	421	7	49	424
Vegetables	197	53	6,642	20	133	982
Unfarmed land	344	n.a.	n.a.	n.a.	1,199	2,472
Total	34,485	130,593	307,571	47,945	253,570	300,319

Land-use areas and environmental outputs do not differ between baseline scenarios. n.a. means data do not exist for unfarmed land. Negative values in greenhouse gas (GHG) emissions or sequestration column refer to sequestration. The total GHG emissions and sequestration are net GHG emissions

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Declarations

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