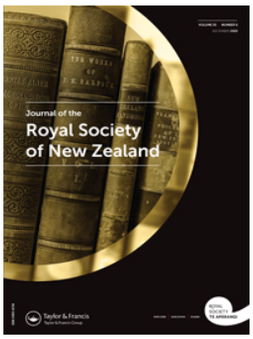

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Are there clear benefits from diversification of land use: a review and preliminary meta-analysis?

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ABSTRACT

Diversified farming systems are often considered more resilient and environmentally sustainable than monocultures. However, their performance on key environmental and economic outcomes remains poorly defined across different contexts. We reviewed the literature and examined data from 277 sites, primarily in New Zealand, regarding the merits of land-use diversification. We tested the hypothesis that nitrogen (N) and phosphorus (P) losses to freshwater (kg/ha), greenhouse gas (GHG) emissions, and job creation differ between farm and catchment scales and that diversification can reduce these environmental losses. Our findings indicate that, contrary to expectations, N losses were higher in diversified systems compared to monocultures at farm scale, and catchment scale. This increase was largely attributed to land-use changes and cultivation practices. However, the total number of jobs was higher in diversified systems at both scales. Although heavily context-dependent, these observational data provide a rationale to determine the conditions under which diversification can improve environmental and economic outcomes. Beyond biophysical conditions, additional challenges in implementing diversification lie in the phasing and implementation of catchment policies at the farm scale, robust supply and value chains to adapt to market demands, and the need to develop and implement technology fit for varied (and diversified) farm systems.

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Jobs; greenhouse gas; nitrogen; phosphorus; profit; diversification; farm system

Introduction

Many policy analysts and academics have hypothesised that diversified agricultural enterprises are central to improving economic and environmental performance (Hanson et al. 2008; Singha et al. 2012; Zanzanaini et al. 2017; Martin et al. 2020; O'Brien et al. 2023). One of the key assumptions is that products produced as monocultures have poorer environmental performance than those produced in diverse systems (Pearson 2007; Hanson et al. 2008; Martin et al. 2020). However, these hypotheses and assumptions

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are problematic, as the definitions of a monoculture or diverse system vary by jurisdiction, and sometimes with space and time. These definitional inconsistencies make it difficult to directly compare the performance of monocultures and diverse systems, leading to a lack of empirical clarity on whether diversification consistently delivers environmental or economic benefits, while existing research often assumes diversification leads to improved outcomes, systematic comparisons remain limited. Current research on agricultural diversification often assumes that diverse systems outperform monocultures in terms of environmental and economic outcomes. However, there are few direct comparisons between these two systems. While some studies have assessed individual performance metrics (e.g. Greenhouse Gas Emissions, nutrient losses, profitability) in isolation, few have comprehensively compared the trade-offs between monocultures and diversified systems under similar conditions (Pearson 2007) (Hanson et al. 2008) (Martin et al. 2020). Furthermore, definitions of diversification vary widely across jurisdictions and spatial scales, making it difficult to draw consistent conclusions.

This review addresses these gaps by evaluating how diversification affects key environmental and economic performance indicators. We synthesise findings from both national and international studies using a common set of metrics to compare monocultures and diverse systems at the farm and catchment levels. Unlike previous research, this study evaluates farming systems using multiple performance measures: GHG emissions, nutrient losses, job creation and economic viability. Additionally, we assess how the spatial scale of diversification influences outcomes, a factor that has been largely overlooked in previous studies.

To effectively assess diversification impacts, it is essential to first establish a clear and consistent definition of what constitutes a monoculture versus a diversified system. However, these definitions vary widely across different classification frameworks and geographic contexts. For example, an international classification system (Hendrickson et al. 2008) defines diversification as the presence of three or more crops or livestock. In New Zealand, farm systems are usually broken into sectors, such as sheep and beef, dairy, or arable, which may vary in size from year to year. However, because many sheep and beef farms also support dairy and produce crops (e.g. for forage or grain), they are classified by this international definition as diverse but viewed domestically as monocultures. In another example, it is assumed that the environmental performance of confined animal feeding operations (CAFO) under dairying conditions is poor owing to high nutrient excesses from large animal numbers and nitrate leaching when manure is applied to the land. However, if excess manure is transported to other farms and only in areas where it is needed, losses of nitrogen per unit of production can be lower than for a dairy farm where animals graze year-round (Dardonville et al. 2020; McDowell et al. 2022a). This is because CAFO farmers can choose where farm manure is to be applied, but in grazed farms, cows must graze in all farm areas (including those prone to high nutrient loss). Over time, animals may enter or leave the farm, and different crops may grow. Depending on their match with soil type, environmental performance may be affected. For instance, the practice of taking stock from other farms to graze them on forage brassicas can double the nitrogen leaching of the receiving area compared to pastures (McDowell and Houlbrooke 2008). These examples highlight the difficulty of assessing environmental performance based on a given definition of the enterprise type.

The problem of definition also exists with regard to spatial scale. At the catchment scale, for example, there can be a mix of land uses, but specialisation can occur where the land is suited to a particular land use or climatic constraints can be removed by infrastructure (e.g. irrigation). While a diverse catchment may have a wider array of jobs, a more specialist catchment may have greater profitability, but potentially also greater job diversity if, for example, infrastructure requires maintenance.

Although defining diversification can be challenging, it is clear the concept varies. The hypothesis that diversification improves performance should be tested, as this term is being used in policy. For example, the Agricultural Diversification Scheme in Wales is a capital grant scheme that encourages and supports the establishment of new agricultural enterprises on farms, or through existing or novel niche enterprises (Welsh Government 2022). The goal is to build economic resilience by developing multiple income streams, reducing reliance on traditional enterprises, and responding to new market opportunities. Another example of policy-driven diversification is New Zealand's contribution to the development of the Indo-Pacific Economic Framework for Prosperity, which was set as the first international supply chain agreement of its kind. This agreement encompasses several key objectives, including the goal of enhancing diversification (New Zealand Foreign Affairs & Trade 2024).

In this paper, we review different definitions of diversification and monocultures, highlighting those that are useful for farmers and policymakers, with a focus on New Zealand. After collating data from national and international examples of monoculture and diverse systems, a common set of metrics was used in a preliminary meta-analysis to summarise the performance of monocultures and diverse systems at the farm and catchment scales. These spatial scales are used because they align with actions to achieve objectives, such as industry initiatives and national policies to reduce farm greenhouse gas emissions or improve water quality (Ministry for the Environment 2019, 2020). While some of these actions are beginning to be implemented regionally, such as the One Plan (Horizons Regional Council 2024) in New Zealand, which integrates land use, environmental management, and economic planning, wider decisions about factors such as land use change are likely to arise within the next 5–10 years and should be guided by the need (or not) to diversify. Finally, we use our observations to comment on the future challenges facing diversification.

Specialised monocultures vs diversification

By 2050, the global population is estimated to reach 10 billion, requiring an increase in food production of 70% (Kremen et al. 2012). To address this growth, agriculture has intensified on existing land and new land has been brought into production; one modelled scenario shows agricultural land expanding from the current 5.1 billion ha to 5.4 billion ha globally by 2030 (Wirsenius et al. 2010). The quest for increased production often leans heavily on monocultures and specialised farming practices. This shift towards specialisation of monocultures has been enabled by industry knowledge that enhances land performance, alongside price support policies and centralised marketing strategies designed to mitigate risks and stabilise the agricultural sector (De Roest et al. 2018). Mechanical and technological advancements, coupled with the availability of affordable external inputs, such as fertilisers, have allowed specialised farms to increase

yields by using larger machinery and expanding field sizes with smaller workforces. As a sector, a 1.6% increase is needed in land used for dairy production between 2020 and 2029 to meet growing global demand for dairy products (OECD/FAO 2020). New Zealand stands out as a prime example of land use intensification, with a near doubling of dairy herd sizes over the past three decades and a significant increase in dairy numbers (Moller et al. 2008; Scarsbrook and Melland 2015; Dairy NZ 2016; Julian et al. 2017; Statistics New Zealand 2023). However, this intensification has raised concerns regarding its environmental impact, including the effects on freshwater quality, animal welfare, and greenhouse gas emissions (Moller et al. 2008; McDowell et al. 2022a).

As a result of intensification, traditional family farms have become less common (Björklund et al. 1999). However, Graeub et al. (2016) note that small-scale family farms play a crucial role in supporting farmer livelihoods and environmental sustainability, suggesting that they may be more profitable per hectare, more resilient, generate more local jobs, and enhance biodiversity. Other studies also suggests that smaller, family-owned farms tend to be more diverse (Hanson et al. 2008; Wuepper et al. 2020), as a strategy to mitigate the risk associated with price volatility, production variability, technological uncertainties, and dynamic policy landscapes (Moschini and Hennessy 2001). This view was reinforced by Hanson et al. (2008), who challenged the assumption that economic factors dictate diversification decisions, citing examples in Texas and Western Australia, where farmers opted for diversification to capitalise on opportunities in the market, improve access to resources, and create greater employment opportunities (Joshi et al. 2004). This research resonated amongst stakeholders, who often cite diversification as a means of improving freshwater quality and mitigating climate change. Indeed, Cradock-Henry et al. (2020) highlighted farmers' and landowners' diversification as an adaptation strategy to overcome the challenges that they face to remain profitable and sustainable over the long-term. In the Westpac New Zealand Agribusiness Climate Change report (Saunders et al. 2022), a key mitigation strategy was to adopt low emission practices, access new markets, and enhance resilience through diversification of the agricultural landscape. Millar (2024) reports that farmers' motivations for diversification are driven by a focus on environmental sustainability, climate change impacts, future resilience, and financial considerations.

What are diverse enterprises, and how can their performance be measured?

Diversification is a confusing concept because of the various terms used to describe it (Table 1). However, for diversification to be meaningful to policy, landowners, and supply chain actors in meeting environmental or economic targets, its definition must be clear, meaningful, and measurable. This would enable an objective assessment of the performance of diverse systems compared with single enterprise systems.

The literature often associates diversification with benefits, such as enhanced resilience (the capacity to withstand shocks and recover from adverse events), reduced vulnerability (the extent to which a system is affected by stress), and increased robustness (the ability to maintain desired outputs) (Dardonville et al. 2020). However, these concepts have rarely been quantified or explored in detail, resulting in inconsistent definitions across jurisdictions. Hendrickson et al. (2008) proposed a hierarchy for diverse

Table 1. Key terminology used in this review.

Term	Definition
Monoculture	Matthews (2014) defines monocultures as 'industrialised agriculture that in the short term provides an economic return but the economic return becomes less important when you consider the long-term ecological impact and loss of diversity is higher under a monoculture'. Franco et al. (2022) defines a monoculture in two parts (1) that it can be extended in time (such as tree crops) and (2) that it can be reduced by inserting alternative crops. They also describe monocultures at a farm scale as the repeated cultivation of the same plant species for several years. This highlights the high level of specialisation on a single crop. Economic theory describes monocultures as the specialisation or a concentration of resources to produce a single or a narrow range of products at high level of efficiency (Sekyi et al. 2023).
Mosaic	A mosaic, as defined by Paul et al. (2017) in the context of integrating trees, is defined as compartments of land use within a farm.
Diversification	Diversification as defined by Bayne and Renwick (2021) involves the production of multiple products to manage risk and market downturn. Sometimes this is shown through one area of the property been used for a 'niche' product.
Mixed Farming	A system which involves growing of crops and livestock at the same time. (Bayne and Renwick 2021).
Intensified Diversification	As defined by Bayne and Renwick (2021) producing more products off the same piece of land with minimal additional inputs.
Diversified Specialisation	Defined by Bayne and Renwick (2021) this occurs when landowners become specialised land managers who provide services to multiple landowners. This approach allows the entire property to be used for various land uses, with specialist managing each specific area.

farming systems, suggesting that a farm can be diverse if it incorporates three or more species of crops or livestock such as cattle, red deer, sheep, and forage crops. This study, cited 130 times as of 2024 (Elsevier 2024), provides a commonly adopted definition of diversification, but is not without ambiguity. For instance, this definition would see many New Zealand pastoral farms as considered diverse internationally but not domestically.

The literature consistently recognises that diversification occurs at various scales and may benefit different stakeholders in different ways. For example, to achieve future water quality objectives at the catchment level, diverse catchments could include fields and farms with a range of contaminant losses from low to high. In this scenario, policy set at the catchment scale is actioned at the farm scale as a resource limit (e.g. kgs of N $\text{lostha}^{-1}/\text{yr}^{-1}$). Within a farm, losses and actions to remediate them could be attributable to a few or many fields, benefiting or burdening farmers differently from year to year. To account for variations, we defined diversification at the farm-scale as an individual enterprise producing three or more agricultural products within a defined cadastral boundary and at the catchment-scale as three or more enterprises within or across cadastral boundaries within a catchment. The spatial scale may also expand to encompass regional and national scales where policies can be formulated, and trade negotiations take place.

A range of metrics has been proposed to measure performance across spatial scales. To align farmers with policy, most regulators (on advice from numerous researchers) have converged on a standardised set of metrics such as acceptable losses of nitrogen [N], phosphorus [P], faecal indicator bacterium - *E. Coli*, sediment, GHG emissions, profitability, and job number and type (Dymond 2010; Daigneault et al. 2016; McDowell et al. 2022b) (see also Table 2). These metrics not only allow farmers and policymakers to assess performance from the farm to catchment scale but may also allow for comparisons across jurisdictions. Table 3 summarises selected global policies and their corresponding metrics. As of 2024, in New Zealand's National Policy Statement for

Table 2. Description of each performance metric.

Metric	Definition
N Loss (as nitrate-N)	Nitrogen Losses from the entire farm, including all inputs from farming enterprise and structures (i.e. imported feed, runoff blocks). It will be nitrate leaching loss (S.F Ledgard et al. 1997).
P Loss (in surface runoff and leachate)	Phosphours loss will be focused on those losses due to runoff (including surface and sub-surface losses) but will not include deep drainage and mass movement (McDowell et al. 2005).
Greenhouse Gas emissions (GHG)	Greenhouse Gas(GHG) emissions will be the total emissions from the farm (Methane, Nitrous Oxide, CO2).
Profit	EBITDAR – Earnings before interest, taxes, depreciation, amortisation and restricting or rent costs.
Job Number	The job number is the number of jobs created per land use type (Full Time Equivalents [FTE] per 10ha of land use) Land Water People (LWP) (2022).
Job Type	Will include jobs such as: • Owner • Lessee • Farm Manager • Farm Hand • Advisor (include fertiliser rep, stock, processor) • Contractors

Freshwater Management (NPSFM) the Ministry for the Environment (2020) outlines targets for acceptable concentrations of N, P, sediment, and *E. coli* in freshwater. The Climate Change Response Act (2019) targets net emissions (as $CO_{2\text{-eqivalents}}$) to zero by 2050 and reducing biogenic methane to 24–47% below 2017 levels by 2050. Overseas, Ireland has set targets for reducing GHG emissions (as $CO_{2\text{-eqivalents}}$) by 51% and monitors nitrate-N in freshwaters (Government of Ireland 2021). Policy in the US focuses on reducing the loss of N and P from land to freshwaters (United States Environmental Protection Agency 2024), while the UK uses incentives to reduce GHG emissions and nitrate-N losses from land to water (UK Government 2023). Europe cites reductions in GHG emissions, and *E. coli*, N, and P losses from land to freshwaters through the Water Framework Directive (European Commission 2020), although their farm to fork strategy (Tomkins et al. 2023) also focuses on pesticides.

Using these metrics, we can assess how diversification affects performance across temporal scales (from annual to decadal) and spatial scales (from farm to catchment). This allows us to test hypotheses, such as whether nitrogen (N) and phosphorus (P) losses to freshwater, greenhouse gas (GHG) emissions to air and job numbers are higher at the farm scale than at the catchment scale, and whether diversification can help improve performance.

Methods

To investigate the performance of monoculture and diverse systems, we conducted a search of peer-reviewed, published literature using keywords (Figure 1), and after applying several screening filters, obtained measured or modelled data for N, P, GHG emissions, profitability and job numbers under different systems (monoculture or diverse) and scales (farm or catchment). Catchment-scale studies were included to assess how diversification influences environmental and economic outcomes beyond individual farm boundaries. The catchment scale provides a broader perspective on the effects of nutrient attenuation, cumulative land-use effects, and the interactions between different

Table 3. Key targets and metrics identified in international policy from jurisdictions trading with New Zealand.

Policy or Strategy	Key Targets	Metrics Measured
Europe		
Farm to Fork Strategy (European Commission 2020) (falls out of the European Green Deal) (Tomkins et al. 2023).	• Reduce environmental and climate footprints, to ensure the food system is resilient. • Reduce 50% use of chemical pesticides and pesticides by 2030 • Reduce nutrient losses - N and *P* loss by 50% through integrated nutrient management action plans. Reduction of at least 20% of fertiliser use by 2030. • 25% agricultural land under organic farming by 2030. • Reduction of 50% of sale of antimicrobials for farmed animals and in aquaculture 2030 • Reduction in chemical pesticides • Tax incentives (i.e. member states can target rates to support things like organic fruit and vegetables). • Price of food reflects real cost in terms of natural resources.	• GHG emissions • N and *P* Loss which are statutory management requirements. These are diffuse sources of *P* and nitrate loss.
European Water Framework Directive	Water Framework Directive (WFD) – 45 new and 8 previously established targets that must be meet.	• N and *P* Loss
Nitrates Directive	Requires EU states to monitor quality of waters, particularly those waters that have a concentration of more than 50 mg/l of nitrates.	• Nitrate-N
USA		
Clean Water Act (CWA)*	Within the CWA, the United States Environmental Protection Agency (EPA) has formulated national recommendations for water quality criteria pertaining to pollutants present in surface water.	• Nutrient N and *P* Loss. Bacteria, Biological, Chemical,
Farm Bill 2018	Governs an array of agricultural and food programmes. This is not a permanent legalisation but is renegotiated every few years.	
National Pollutant Discharge Elimination System (NPDES) – Animal Feeding Operations	Regulates point sources of water pollution, with the goal of improving water quality.	• Nutrient N and *P* Loss
UK		
Environmental Improvement Plan (UK Government 2023) • Nitrate Pollution Prevention Regulations 2015	Plan that builds on existing 25 Year Environmental Plan and the Environment Act. Aiming for between 65 –80% of landowners and farmers to adopt 'nature friendly farming' on at least 10–15% of their land by 2030. (UK Government 2024)	• Water Quality (Nitrates) and Supply, Clean Air, GHG Emissions,
25 Year Plan	Green Future, focusing on clean air, clean and plentiful water, thriving plants, reduced risk from environmental harm, using resources more sustainably.	• GHG Emissions, Nitrate-N, *P* and sediment
Ireland		
Climate Action Plan of 2021	51% reduction in overall GHG emissions by 2030.	• GHG emissions
Water Services Policy Statement 2018–2025	First policy statement prepared under the Water Services Act 2017	• Nitrogen
Environmental Protection Agency (EPA) – Nitrates Action Programme		• Nitrate-N

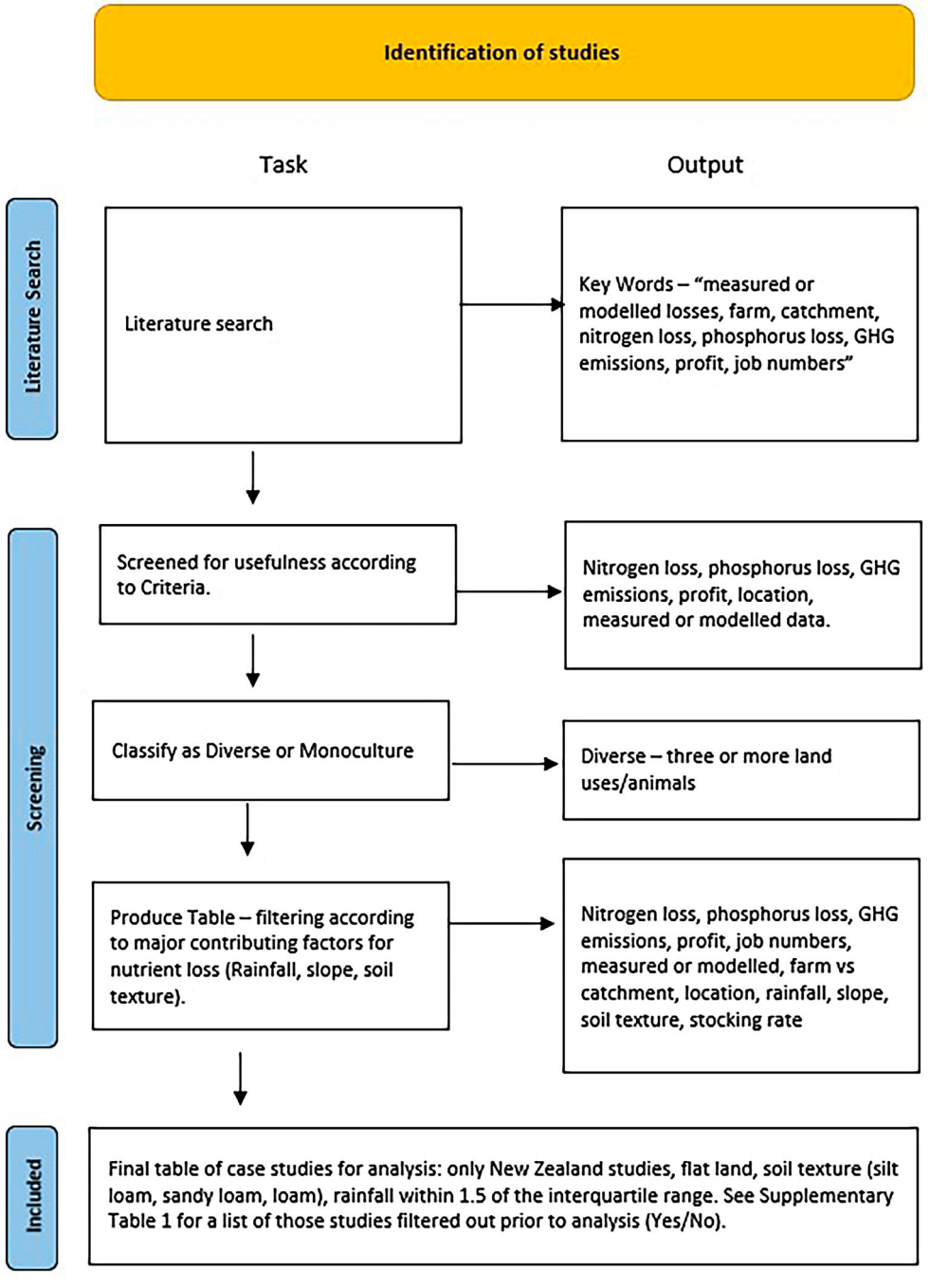

Figure 1. PRISMA flow diagram showing the workflow used to obtain and screen published data.

enterprises. Examining data at this scale allows us to evaluate whether diversification reduces negative environmental impacts (such as nutrient losses and GHG emissions) and supports regional economic development by creating job opportunities and fostering integrated land-use strategies. We only included modelled estimates of N and P loss (kg

ha^{-1} yr^{-1}) from the following models that had been calibrated and verified against observed data: Annual P Loss Estimator (APLE) (Vadas et al. 2015); Agricultural Policy Extender (APEX) (Mason et al. 2020); Agricultural Production Systems Simulator (APSIM) (Holzworth et al. 2018); Dairy Forage System Model (DAFOSYM) (Rotz et al. 1989); DeNitrification-DeComposition (DNDC) (Li et al. 1992; Deng et al. 2015); Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Leonard et al. 1987); Integrated Farm System Model (IFSM) (Rotz 2018); Nitrate Leaching and Economic Analysis Package (NLEAP) (Shaffer et al. 1991); and OVERSEER (AgResearch 2016). Overseas studies were included if the enterprise was managed in a way comparable to New Zealand conditions (e.g. forestry, arable cropping, and horticulture), whereas those with significant differences such as pastoral enterprises, were excluded.

The data were natural log transformed because of skewed distributions. The total dataset captured 277 studies (Supplementary Table S1, Figure S1), covering a variety of land uses and metrics, albeit with varying observation counts per metric. The temporal data were averaged. One-way analysis of variance was conducted to evaluate differences in some metrics based on jurisdiction (international vs New Zealand). Large differences and variations in metrics for international studies, together with their small sample sizes (<25% of the data), led to their exclusion from further analysis.

After removing the international studies, the total number of studies decreased to 194. To ensure consistency in factors influencing nutrient loss, further screening was applied. The analysis was restricted to studies conducted on flat land (0 – 7°), reducing the total to 180. Additional filtering removed studies that fell outside 1.5 times the interquartile range for rainfall (eliminating two more studies) (Burkitt et al. 2016) and those with extreme stocking rates in pastoral systems (Vibart et al. 2015). Soil texture classifications were also standardised using S-Map (Landcare Research n.d-b) or the Fundamental Soil Layer (FSL), (Landcare Research n.d-a) focusing on loam, sandy loam, or silt loams. This final screening resulted in a total of 121 studies (Figure 2) (McDowell et al. 2017; Simelane et al. 2024).

In addition to deriving descriptive statistics, we conducted an analysis of variance contrasting metric means by scale (farm vs catchment) and system (monoculture and diverse) and for the interaction of scale by system, each with a minimum dataset of six observations. Descriptive data for each metric are given in Table 4 and the contrast of the means is shown in Table 5.

Results

There were differences in the number of systems between scales: 16 monocultures and 8 diverse studies at the catchment scale, 85 monocultures and 12 diverse at the farm scale, post-screening. However, most studies were conducted on flat land (92%) and silt loam soils (28%) (Table S1). Additionally, the rainfall (Table 4) was not statistically different between the scales. These filters aimed at constraining biophysical parameters but will have had little effect on constraining management.

After constraining the data, the analysis of variance indicated that mean N losses were greater at the farm scale than at the catchment scale but showed no difference for any of the other metrics (Table 4; Figure 3). Similarly, diverse systems appeared to exhibit greater mean N loss and jobs than monocultures but lower mean P losses (Table 4;

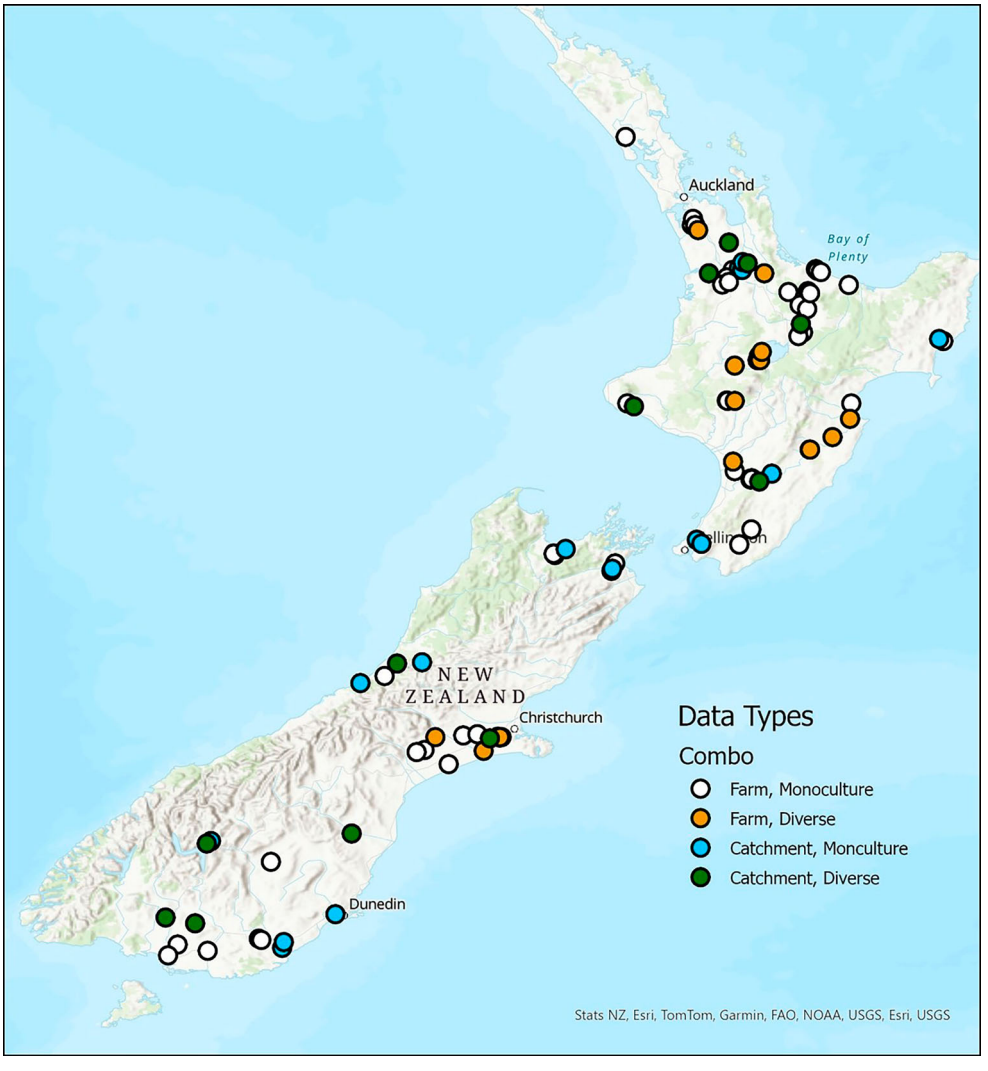

Figure 2. System and Scale of New Zealand measured and modelled data sources.

Figure 3). Sufficient data were only available to contrast the interaction of the system and scale for N loss, but no difference was noted (Table 5). No significant differences were noted in mean GHG emissions. Similarly, there were no statistically significant differences in profitability between monocultures and diversified systems at either the farm or catchment scale.

Discussion

It is important to place these findings in this context. It is plausible that any differences between systems or scales may be caused by the geographic mix of data points (e.g. from Northland to Southland), or other factors, such as climate. However, at the catchment scale, the number and spread of diverse farms were similar to those of the monoculture farms (Figure 2). There was a disparity in the number of systems at the farm scale;

Table 4. Descriptive statistics for scale (farm or catchment), system (monoculture or diverse).

Variable	Scale	System	N	Mean	StDev	Minimum	Median	Maximum
Rainfall (mm yr^{-1})	Catchment	Diverse	8	891	307	647	771	1520
		Monoculture	16	1098	253	719	1180	1520
	Farm	Diverse	12	1078	331	639	950	1589
		Monoculture	85	1054	314	627	1056	1877
N loss (kg N ha^{-1} yr^{-1})	Catchment	Diverse	7	19.0	12.4	7.0	17.5	39.5
		Monoculture	9	8.3	8.2	0.1	9.0	26.0
	Farm	Diverse	12	35.5	36.8	7.0	25.0	145.0
		Monoculture	62	25.7	21.4	0.7	21.0	89.0
P loss (kg *P* ha^{-1} yr^{-1})	Catchment	Diverse	5	0.48	0.32	0.10	0.40	0.90
		Monoculture	14	0.55	0.55	0.03	0.40	2.00
	Farm	Diverse	7	0.16	0.11	0.05	0.10	0.33
		Monoculture	27	1.15	1.23	<0.01	0.80	5.15
Profit ($ ha^{-1} yr^{-1})	Catchment	Diverse	0	*	*	*	*	*
		Monoculture	2	3150	778	2600	3150	3700
	Farm	Diverse	1	3535	*	3535	3535	3535
		Monoculture	24	13090	27439	20	4365	116000
GHG Emissions (T ha^{-1})	Farm	Diverse	4	5.8	6.6	1.8	2.9	15.6
		Monoculture	32	49.3	124.3	2.6	9.8	506.6
Jobs (FTE ha^{-1} yr^{-1})	Catchment	Diverse	8	39.3	37.3	0.6	42.9	102.5
		Monoculture	14	12.2	23.6	<0.1	0.2	62.0
	Farm	Diverse	4	14.6	9.5	0.4	18.8	20.5
		Monoculture	64	2.3	3.2	<0.1	0.9	14.3

* = No data.

Table 5. *P* values for the contrast of log-transformed data by scale (farm or catchment), system (monoculture or diverse) and the interaction of scale and system.

Variable	Scale	System	Scale x System
N loss (kg N ha^{-1} yr^{-1})	0.002	0.003	0.086
P loss (kg *P* ha^{-1} yr^{-1})	0.970	0.005	0.002
Profit ($ ha^{-1})	0.824	0.943	*
GHG emissions (T ha^{-1})	*	*	*
Jobs (FTE ha^{-1})	0.932	0.001	0.629
Rainfall (mm yr^{-1})	0.995	0.643	0.400

* = insufficient data for comparison.

however, both systems had similar geographic distribution. This suggests that both the scales and systems are exposed to comparable biophysical conditions.

Our findings for nitrogen (N) losses were consistent with our hypothesis that losses are lower at catchment scale than at farm scale. This difference is likely due to in-stream attenuation, where N is removed through biotic or abiotic uptake, as well as the inclusion of more non-agricultural land at the catchment scale that would dilute N losses (McDowell et al. 2021). However, we noted that N losses were higher in diversified systems comparted to monocultures. Gross nitrogen mineralisation is influenced by land use, management, and climate, which may help explain variability across systems (Elrys et al. 2021). Practices such as crop rotation or shifts in livestock can accelerate mineralisation processes or disturb nutrient balances, especially when cultivation follows pasture or forage crops. These transitions may temporarily elevate nitrogen losses, particularly if fertiliser inputs or stock density are not adjusted accordingly. (Moller et al. 2008) (Ledgard et al. 1999) (Di and Cameron 2002). Further investigation is needed to distinguish which types of land-use change are most influential.

In contrast to N losses, P-losses were lower in diversified systems than monocultures. This is likely due to the strategic placement of low P-loss land uses in areas vulnerable to

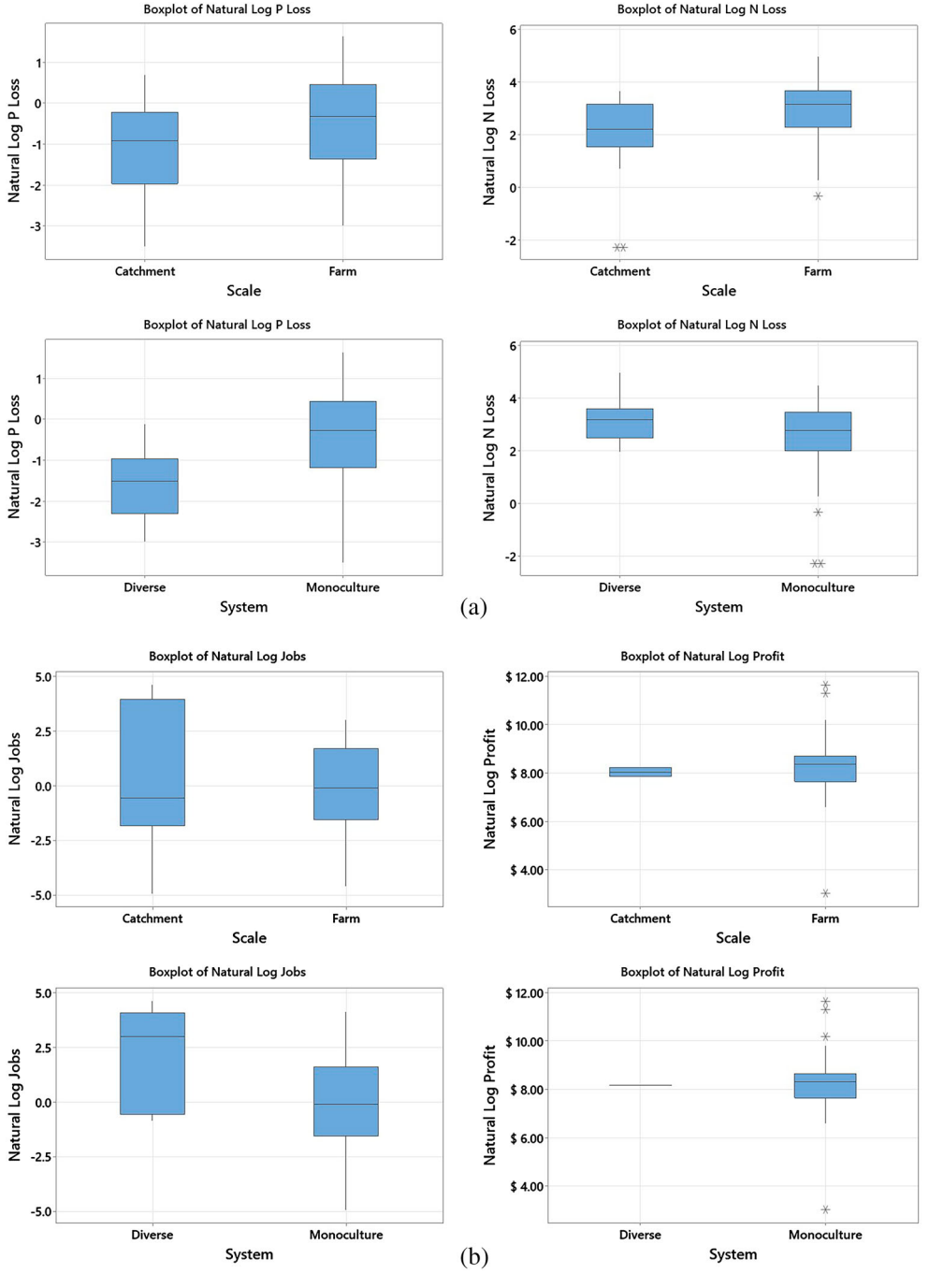

Figure 3. Box plots summarising observed nitrogen (N) and phosphorus(P) losses from land to water and job counts and profit created for farms and catchments and diverse and monocultures in New Zealand. The top, middle and bottom of the boxes represent the 75, 50 and 25th percentiles, with the top and bottom whiskers representing the 95th and 5th percentiles, respectively.

P runoff, such as the use of cover crops to reduce erosion – an approach that monocultures may lack flexibility to adopt. (Kaspar and Singer 2011). Given the limitations of our dataset, we cannot fully exclude alternative explanations for these patterns. Further research is needed to confirm these mechanisms and refine our understanding of how diversification influences nutrient losses across scales.

Another finding was that job numbers were greater at the catchment scale (per unit area) than at the farm scale. As scale increases and the likelihood of different farms being present increases, there is a need for a greater diversity of job types. Unfortunately, we do not have data to infer the types of jobs created.

While shifting to diversified systems presents challenges, these findings also highlight potential benefits that warrant further exploration. The observed differences in N and P losses between monoculture and diversified systems suggest that land-use diversification may not always lead to immediate reductions in nutrient losses at the farm scale. However, at the catchment scale, in-stream attention and the presence of mixed land uses appear to contribute to lower overall N losses, supporting the hypothesis that diversification can have positive water quality outcomes when implemented strategically. Additionally, the higher job numbers associated with diversified systems indicate that they may provide greater employment opportunities, potentially contributing to rural economic resilience. These findings suggest that rather than viewing diversification as an all-or-nothing approach, its benefits may be realised more effectively through carefully planned transitions at the farm and catchment scales. Future research should focus on identifying management strategies that optimise the environmental and economic advantages of diversification while mitigating potential trade-offs.

While this study focused on the effects of diversification on water quality, GHG emissions, and job numbers, diversification has also been widely recognised for potential biodiversity benefits. Published literature suggests that diverse landscapes can enhance habitat availability, promote species richness, and improve ecosystem services, which are critical for long-term sustainability. (Kremen and Miles 2012) (Wuepper et al. 2020). Although biodiversity metrics were not assessed in this study, future analyses could integrate these considerations to provide a more comprehensive evaluation of the environmental trade-offs and benefits of diversification.

To determine if the differences inferred by the collected data were real, we would likely need to model the performance of different systems to investigate their behaviour under varying conditions. Such modelling would control and contrast the performance of different farm systems to graduated changes in biophysical conditions (e.g. an increase/decrease in rainfall in 10% total rainfall), thereby generalising the relationships between diversification, performance, and environmental impact. Nevertheless, these data suggest that better performance metrics from diverse over monocultural systems may not be discernible where there is existing wide variation in biophysical conditions or management practices such as occurs in New Zealand.

Although this study adopted a working definition of diversification as three or more agricultural products or enterprises, further work may be needed to test whether this threshold is appropriate for New Zaland's unique pastoral systems. It is possible that environmental outcomes may not scale linearly with the number of enterprises but rather depend on their functional differences and alignment with soil and climate characteristics. Modelling future scenarios of diversity could help refine this understanding and offer more targeted guidance of land-use planning.

Shifting agricultural practices: from supply to diversification

While we have shown that data supporting the benefits of diversification are inconsistent, there are many other challenges associated with implementing diversified agricultural systems. We explore these below.

Lack of evidence

The use of varying terminology to describe diversification complicates informed decision-making for both policymakers and individual landowners. This lack of clarity contributes to the uncertainty that landowners and policymakers face when making long-term land use decisions. One solution to this is to generate more data at a local scale to better understand the biophysical variations (Bouma et al. 1998). To address this gap, more high-resolution data at a local scale are needed, particularly detailed soil information at the farm level. This is crucial for assessing land suitability for different enterprises and understanding how diversification impacts environmental and economic outcomes. One approach to generating such data is through integrated modelling frameworks that can simulate the interactions between different enterprises at the farm scale. These models can assess the environmental impacts (e.g. nutrient loss, GHG emissions) and economic viability of diversified systems, providing valuable insights for policymakers and landowners navigating land-use decisions (Daigneault et al. 2018). Beyond soil and climate data, there is also a need for long-term studies assessing how diversified land use systems impact economic viability, resilience and environmental performance over time (Kremen et al. 2012). For example, research in Europe has shown that diversified agroforestry systems can enhance biodiversity and carbon sequestration while maintaining profitability (Torralba et al. 2016)

Policy and regulation

As discussed earlier, environmental policies are commonly enacted at the catchment scale but implemented at the farm scale. However, these policies can be out-of-phase, operate on different spatial and temporal scales, or are antagonistic to each other. A clear example is New Zealand's National Policy Statement for Freshwater Management (NPS-FM), which sets nutrient limits at the catchment level but requires compliance at the farm scale. This has created significant challenges for landowners in catchments dominated by high-intensity land uses, as individual compliance can be costly and difficult to measure against catchment-wide outcomes (Ministry for the Environment 2023a; McDowell et al. 2024). Another example relates to Cyclone Gabrielle which impacted the East Coast of New Zealand in 2023 resulting in major road damage and 300M tonnes of sediment and associated forestry slash being washed into rivers and out to sea (McMillian et al. 2023). Some have suggested that because of the short clear-fell rotations (~25 years) typical of *Pinus radiata* plantation forestry on shallow and erosion-prone soils of the East Coast region, retirement into natives is a better option (Lawrence 2022; Gisborne Herald 2023; McMillian et al. 2023). However, many people are employed in the forestry sector, and a shift to natives would result in significant jobs losses. By introducing many policies simultaneously and out of phase, the complexity of the required responses can lead to uncertainty and inaction by landowners. Therefore, an integrated solution is required. While plans have been

considered at the farm scale (McDowell and Kaye-Blake 2023) to address water and GHG losses (e.g. freshwater farm plans (Ministry for the Environment 2023b), Ministry for Primary Industries (MPI) He Waka Eke Noa (2023), and supplier schemes such as Synlait's Lead with Pride (Synlait 2023) and Fonterra Tiaki (Fonterra 2020), there is less evidence of integrated planning at the catchment scale (Parliamentary Commissioner for the Environment 2023). Indeed, a report by Environmental Communications Ltd (2010) highlighted capacity, co-ordination, and management problems across spatial scales as key barriers to Integrated Catchment Management.

Market access and consumer preferences

In response to changing consumer preferences, some companies, such as Fonterra with its CarbonZero milk (Fonterra 2020), have sought to offer premium products to markets such as the European Union by emphasising a low carbon footprint by diversifying dairy farms with different low GHG practices. However, processors are increasingly required to differentiate themselves in the market while complying with new trade requirements, which puts constant pressure on the systems to adapt. Beyond regulatory compliance, assurance programs such as NZFAP + (New Zealand Farm Assurance Programme Plus) (New Zealand Farm Assurance Programme 2025) are taking a proactive approach to consumer demand by going beyond minimum market requirements. These programs emphasise environmental stewardship, animal welfare, and ethical farming practices, ensuring that New Zealand's agricultural products remain competitive in premium markets.

The increasing demand for carbon-neutral, regeneratively-farmed, and ethically-produced goods highlights the shift from traditional commodity-based agriculture to value-differentiated markets (Saunders et al. 2022). For example, grass-fed beef and dairy, certified under sustainability frameworks, are commanding price premiums in European and North American markets. Similarly, organic and biodiversity-friendly certifications are becoming key drivers in export growth, particularly for horticultural and speciality crop sectors (Reganold and Wachter 2016).

However, the success of these programs relies not only on farm-level adoption but also robust supply chains, market access agreements, and clear verification processes. Global trade policies, such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and sustainability-linked tariffs, may further challenge New Zealand's agricultural exports, making compliance with evolving sustainability metrics an essential aspect of market access (OECD/FAO 2023).

These shifts underscore the need for adaptive farm systems that align with evolving market expectations while maintaining economic viability. Investments in traceability technology, farm certification programs, and diversified production systems will be critical in ensuring long-term competitiveness in premium export markets.

Implementing change

When diversifying across multiple farms, it is crucial that this is phased over time and space to ensure that catchment outcomes are met. In Ireland, for example, government-supported transition programs helped sheep and beef farmers integrate agroforestry practices over a decade, balancing environmental goals with economic stability

(Wreford et al. 2010). A similar phased approach in New Zealand could help minimise short-term economic risks while allowing ecosystem benefits to accumulate over time. The implementation must occur in a timely manner with equitable results (Baran-Zgłobicka and Zgłobicki 2012). However, success may hinge on how we measure the desired outcomes (Davies 1995; Baran-Zgłobicka and Zgłobicki 2012). For example, diversification can be challenging when policies have strict deadlines, require changes before stakeholders have had adequate time to consider trade-offs, or when there is a lag between presenting evidence off change and acting. Furthermore, primary industry groups often prioritise protecting their own sectors and may be reluctant to invest in data collection and monitoring efforts that could enhance their understanding and support diversification (Nguyen and Hens 2021).

Technology influence

Technology has advanced agricultural production via innovations in genetic engineering, plant breeding, precision fertilisation, and new cultivation machinery (Bouma et al. 1998). Emerging technologies, such as digital agriculture, including smart farming, artificial intelligence (AI), robotics, and big data, are poised to further refine agricultural practices by identifying optimal diversification strategies based on factors such as soil type and climate variability (Pinares-Patiño et al. 2009). White et al. (2010) demonstrated that these technologies can enhance the growth and management of pastures and crops, and that smart farming technologies, including drones and sensors, offer more precise farm management and resource utilisation, potentially leading to reduced pollution, greenhouse gas emissions, and input costs through precision agriculture (Walter et al. 2017a). However, these technologies come at a cost and may also be resisted by older farmers. The digital divide between large agribusinesses and smaller family-run farms means that not all farmers can access precision agriculture tools, AI-driven soil monitoring, or blockchain-based supply chain tracking (Walter et al. 2017b). Bridging this gap through subsidies or extension services could support the broader adoption of technology-driven diversification.

Supply and value chains

New Zealand has successfully expanded beyond commodity-driven sectors, such as dairy, red meat, and forestry. Notable examples include Zespri (kiwifruit production) and the wine industry, which have capitalised on niche markets and premium quality to thrive internationally (Zespri 2023). Success stories highlight the potential benefits of strategic diversification. However, attempts to diversify into industries such as saffron and truffles have met with little success in New Zealand. The failure of these industries can often be attributed to supply chain weaknesses, underscoring the challenges of entering niche markets without adequate demand or infrastructure (Sisson 2021). Thus, although diversification holds promise for accessing multiple markets, it must be approached with caution and supported by robust supply and value chains to ensure market viability and competitiveness. Additionally, it should be included in integrated catchment plans to help build economies of scale by identifying where land is available and suitable to reach minimum viable size.

Conclusions

In defining diversification as the integration of at least three or more land uses or livestock, our findings indicate that, at the catchment scale, diversification resulted in lower N losses compared to farm scale. This could be attributed to factors like in-stream attenuation and a higher proportion of non-agricultural land at the catchment scale. However, we also observed that diversified systems tended to lose more N to water, possibly due to the more frequent changes in land use (such as crop rotation or shifts in livestock) compared to monocultural systems.

While these results suggest a complex relationship between diversification and water quality, it is important to emphasise that the data available are insufficient to draw definitive conclusions. Variability in local biophysical conditions – such as climate, soil types, and hydrological factors could be confounding the results. Therefore, while we see evidence that diversification may not automatically result in better water quality outcomes, all we can conclude is that better performance metrics from diverse over monocultural systems are not discernible where there is existing wide variation in biophysical conditions or management practices such as occurs in New Zealand. In other words, although diversification is often advocated as a strategy for sustainable land use, the data currently available do not provide sufficient evidence to confirm that it unequivocally leads to better environmental outcomes, particularly for water quality. The gap in understanding remains, and future studies, including more robust modelling, are necessary to assess the true benefits of diversification.

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