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Understanding land-use transitions in rural areas of the North Island, New Zealand from 1996 to 2018: an intensity analysis approach

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Abstract Land-use change is a key feature of New Zealand's landscapes. Several national land-use assessments show a slowing conversion from pastoral land to exotic forest but did not take the local scale into account. To explore this, we applied intensity analysis to better understand spatial–temporal changes in land use over time in the rural landscapes of the North Island, New Zealand. Land-use maps from 1996, 2008, 2012, and 2018 were used to analyse land changes at three levels: time interval, category, and transition. Results show that most land-use transitions have been decelerating over those periods, and changes in the native forests were dormant. The gains of pastoral land and exotic forests were losses of shrubland during all the time intervals. Patterns of transition vary based on local cases and are primarily influenced by regional policies (e.g., greenhouse gasses emissions related legislations), and environmental conditions (e.g., erosion-prone areas). Furthermore, applying this approach provides insights into how deforestation occurs locally and how land managers influence land-use transitions.

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Introduction

Land-use change has been an essential characteristic of the New Zealand landscapes since the arrival of humans. Forests once covered approximately 82% of the country, but deforestation started approximately 800 years ago after the arrival of Māori and accelerated with European settlement in the late 19th Century (Ewers et al., 2006; McConnell et al., 2021; Wilmshurst et al., 2008). By the late 20th Century, New Zealand's native forests were reduced to 23% of its original land area (Ewers et al., 2006). Several studies have documented the significant land-use changes in rural areas from extensive lowland native forests to agricultural use during the 1950s and entered another major transition—afforestation of exotic forests in the 2000s (Dodd et al., 2008). These transitions from forest to agriculture and vice versa influence many ecological and hydrological functions. Thus, it is necessary to detect the patterns of land-use change to understand and mitigate its negative consequences.

Most of the studies on land-use changes in New Zealand are at the national level (Carter, 2018; Kerr et al., 2007; Whitehead et al., 2021). Nonetheless, land-use changes at the local level can be as crucial

as national-level changes for particular environmental effects (Kerr et al., 2007). Local-scale landscape pattern changes directly affect ecosystem service functions, and analysing them can provide a valuable reference for environmental protection and sustainable land management (Piao et al., 2023; Villamor et al., 2022). According to Príncipe et al. (2022), local-scale factors and their interaction with broad-scale factors explained more variance than broad-scale factors alone. Local-scale factors of land-use change may vary widely among political districts (Ewers et al., 2006). For example, in the Tararua District (Fig. 1), there is widespread concern in the local community that the conversion of pasture to forests for carbon sequestration is large scale and is having negative effects on the environment and community (Collins & McFetridge, 2021). However, there is no local-scale data on the actual size of changes in land use in the district and the speed of change. The lack of accurate information makes it difficult for stakeholders and decision-makers to make informed decisions for their community, and indeed, they may rely on preconceived perceptions and misinformation. Hence, it is essential to capture land use and land cover patterns at the local scale. For this study, we aim to improve our understanding of land changes or transitions in three rural districts of the North Island, New Zealand. These districts were identified by the Forest Flows MBIE research programme (Meason et al., 2020) as having concerns about planted forests and its impact on water availability and quality (Villamor et al., 2025). We applied land-use intensity analysis as a straightforward analysis to understand the transition processes from 1996 to 2018. This study answers the three research questions:

1. Which time intervals show a relatively *slow* or *fast* annual change in area? (*Interval analysis*).
2. Which land categories are relatively *dormant* compared to those *active* during a given time interval? (*Category analysis*); and
3. Which transitions are *targeted* and *avoided* during a given time interval? (*Transition analysis*).

Land-use transitions in New Zealand

Broad-scale rural land-use changes and their drivers are well documented in New Zealand because of their implications for economic and environmental impacts on the country (MPI, 2017). Fetzel et al. (2014) described four key phases of land transitions between 1860 and 2005. The reduction of native forests and cropland growth characterised Phase 1 (1860–1920).

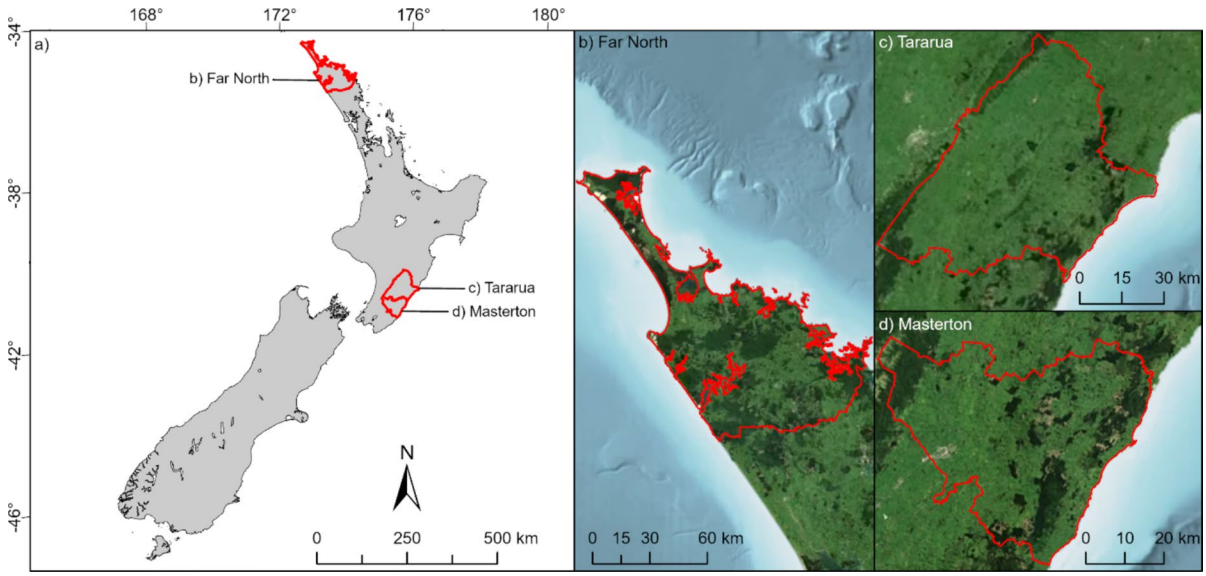


Fig. 1 Location and maps of the three case study districts: **a** Map of New Zealand; **b** Far North; **c** Tararua; and **d** Masterton. (*Source*: LINZ data service)

In Phase 2 (1920–1950), deforestation slowed, agriculture expansion stagnated, and plantations of exotic forests emerged. Phase 3 (1950–1980) described the expansion of managed grassland and plantations. According to MacLeod and Moller (2006), the expansion of agricultural land during the early 1960s was driven by high subsidisation of the farming sector. Phase 4 (1980–2005) was characterised by the return of native shrubland/scrub and a decline in managed grasslands. The removal of farm subsidies triggered these patterns; however, the diversification of agriculture from the 1970s continued until mid-2000 (MacLeod & Moller, 2006).

Several land-use change models and assessment approaches have been developed for New Zealand to understand these patterns and predict the economic and environmental impacts of those land-use changes. Two of the most common land-use models developed for New Zealand are the Land Use in Rural New Zealand (LURNZ) and the NZ-FARM models (Hendy et al., 2018). The LURNZ model is an economic model designed to assess the implications of environmental policies on future land use (including production and greenhouse gasses) and predict land-use changes (Hendy et al., 2007). The NZ-FARM model is a partial equilibrium model to assess the impacts of environmental and agricultural policies on landowners. Furthermore, econometric models were used to explore the drivers of rural land-use change and predict changes and their associated economic and environmental implications (Kerr et al., 2007). Dorner and Hyslop (2014) applied the multinomial logit model to understand the country's slow change in rural land use during 1997–2008. Particularly in forestry expansion, Nagashima et al. (2002) demonstrated the change process by comparing the area, patch number and size, and land-use distribution between 1970 and 1990 in the Nelson region. The study further applied the principal component analysis to understand the process of forest expansion in detail. Whitehead et al. (2021) presented the most recent land-use changes from 1990 to 2016 at the national level and estimated their effect on soil carbon stocks. Accordingly, the largest increases were observed in perennial croplands, high-producing grasslands, and buildings.

For this study, the intensity analysis is applied as another approach to understanding the land transition processes in rural landscapes in three districts of New Zealand during 1996–2018. Developed by Aldwaik and Pontius (2012), the intensity analysis is a mathematical or accounting framework used to express differences within a set of categories at multiple time points (Quan et al., 2020). It focuses on the size and intensity of land change in a hierarchical framework for detecting size, intensity, and temporal stationarity in the time interval, category, and transition level of change using the information in transition matrices. Interpreting the results of intensity analysis is straightforward, with insightful graphical expressions of land changes (Deng & Quan, 2023). In this regard, intensity analysis provides insights into how different types of land are utilised and the level of intensity applied. This information helps make informed decisions regarding resource allocation, such as identifying low-intensity areas or underutilised land that could be repurposed for more productive uses. The advantage of using the intensity analysis approach compared to conventional crosstabulation methods is that it quantifies the contribution of different land categories to land-use change over time (Sang et al., 2019; Yang et al., 2019). The approach was widely applied to understand land transitions affecting food security in China (Quan et al., 2020), regional livelihoods in Ghana (Shoyama et al., 2018), carbon loss in the rubber agroforestry in Indonesia (Villamor et al., 2014), expansion of the built-up and urban areas (Kourosh Niya et al., 2019; Mallinis et al., 2014), an increase in forest areas due to government policy initiatives (Kaptan, 2021), and other applications on six continents (Pontius et al., 2013).

This paper applies the approach for the first time in selected rural landscapes of New Zealand to analyse the current intensity of land-use transitions.

Methods and materials

Case study areas and descriptions

Three districts across the North Island: the Far North, Tararua and Masterton districts (Fig. 1a), were chosen based on the biophysical set-up of the Forest Flows MBIE Endeavour research programme (https://www.scionresearch.com/science/sustainable-forest-and-land-management/Forest-flows-research-programme).

The Far North (Fig. 1b) is New Zealand's northernmost district in the Northland region, with a land area of 7324 km^2 and a population of 65,250 (Statistics New Zealand, 2018a). It is a coastal location with strong winds across the region, particularly around the west coast. This greatly influences rainfall prevalence and frequency as rainfall in the district is typically abundant (averaging 1000–2000 mm annually), highest in winter and lowest in summer (Chappell, 2013). The Far North is also warmer, with mean annual temperatures ranging from 15.5 to 16 °C and a maximum of 28 °C in summer (Chappell, 2013). Thus, drought/dry periods are common in summer, causing a large dependence on rainfall storage by rural communities during winter to prepare for several weeks or months of dry, hot and windy weather with water restrictions (Northland Regional Council, 2012). These fluctuating weather extremes may affect the district's land-use practices considerably. Most of the land is rural. The most significant economic driver from 2010 to 2020 was the agriculture, forestry and fishing industries ($69 million) (Infometrics New Zealand, 2021a) which depends on seasonal changes. Forestry in the Far North is established on two types of sites: Aupōuri dune forests to prevent encroachment of sand dunes onto farmland or hill country initially cleared of forest for farmland (Lucich, 2020). Small portions of original/regenerating native forest are scattered across plantation blocks, especially in riparian areas. The Far North's avocado industry is also among the most prominent in New Zealand—a business requiring large quantities of water for growth. These industries all utilise several land uses, which may lead to various environmental issues such as severe erosion and inundation after extreme rainfall, increased sedimentation, soil contamination, and the salination and depletion of water sources in the district (Far North District Council, 2022).

The Tararua district (Fig. 1c) occupies 4364 km^2 in the southeastern part of the Manawatu-Wanganui region, with a population of 17,943 (Statistics New Zealand, 2018c). This district has fewer climatic extremes, except in higher elevation areas. The topography strongly influences wind direction and speed, giving rise to regular rainfall in the district averaging 750–1000 mm annually (Chappell, 2015). The weather in Tararua is average for New Zealand, with moderate frosts in the winter and pronounced sea breezes in the summer (Chappell, 2015). Significant parts of the district, such as Dannevirke, Norsewood, and Pahiatua, have the largest flat land areas, highly suitable for pastoral and horticultural activities (Tararua District Council, 2021a). Approximately 13% of that land is highly productive, with hilly areas highly suitable for forestry (Tararua District Council, 2021a). However, half of that area is susceptible to erosion (Tararua District Council, 2021b). Agriculture contributes considerably to the district's economy, with over one-third of district workers employed in high-quality stock, wool, meat and dairy production. Around 90% of all holdings in Tararua are represented by sheep, beef and dairy farms and account for 99% of the total stock units (Tararua District Council, 2021a). Some larger industries include meat processing, dairy processing and steel fabrication.

Masterton is one of three districts in the Wairarapa region with a total land area of 2295 km^2 and a population of 25,557 (Statistics New Zealand, 2018b) (Fig. 1d). The climate in this district is primarily driven by seasonal changes with common droughts and extreme storms (Chappell, 2014). The temperature fluctuates in extremes from 20 to 28 °C in summer and below 10 °C in winter and demonstrates considerable interannual variability—an effect derived from a combination of anthropogenic and natural causes (Falloon, 2015; NIWA, 2021). The district is surrounded by the Tararua Ranges and Wairarapa Valley on the west, with hill country in the east (Braaksma, 2010). The eastern hill country is the dominant land responsible for sheep and beef farming (33% of the Wairarapa region) and contains large areas of forestry production (Falloon, 2015). However, 70% of hill country properties contain erosion-prone land, with only 14% on flat, productive land (Cameron, 2016). Thus, the planting of poplars and willows was adopted by rural landowners to provide the necessary erosion control (Cameron, 2016). Masterton's economy is not as dependent on the agriculture, forestry, and fishing industries as the Far North and Tararua, with four non-agriculture industries equally contributing to economic growth between 2010 and 2020 (Infometrics New Zealand, 2021b). The emphasis on urbanising Masterton may strongly aid this diverse economy. The Masterton District Council's vision of transforming Masterton into a 'modern town' will require making land

available to build housing (Masterton District Council, 2021). Additionally, other land uses include *Pinus radiata* (D. Don) woodlots for farm conservation and economic return and manuka/kanuka planting for honey production and increasing soil stabilisation (Cameron, 2016).

Data

There are two publicly accessible national datasets of land use and land cover (LULC) for New Zealand. The New Zealand Land Cover Database (LCDB), developed by Manaaki Whenua—Landcare Research, is a multi-temporal, nationwide thematic land cover classification (Landcare Research, 2020). Five iterations of the LCDB exist, with summer surveys conducted in 1996–1997, 2001–2002, 2008–2009, 2012–2013, and 2018–2019. The classification maps have 35 land cover classes across the mainland and Chatham Islands. With each new version of the database, prior iterations are refined to maintain consistency and ensure compatibility between timesteps. The Land Use and Carbon Analysis System (LUCAS) is a multi-temporal thematic classification of land use developed by the Ministry for the Environment to ensure carbon stock changes and greenhouse gas emissions are reported under Article 3.3 of the Kyoto Protocol (MFE, 2020). The LUCAS has four iterations, with land use in 12 classes available for 1990, 2008, 2012 and 2016.

Both databases use minimum mapping units of one hectare. They are informed by visual interpretation and classification of multi-spectral satellite imagery, namely data obtained from 30 m Landsat, 10 m Sentinel-2, and 10 m Satellite Pour l'Observation de la Terre (SPOT) satellites. The classification from these data was supported by and further refined using ancillary and field data. Each new version of the LUCAS database improves by integrating verified land-cover information derived from the LCDB (Newsome et al., 2018). Both the LUCAS and LCDB datasets contain overlapping classes. For example, both include variants of grassland, settlements, natural forest, cropland, and exotic forest classes. However, the temporal coverage of the datasets is only partly concurrent, with the 2008–2009 and 2012–2013 seasons being the only overlapping timeframes between the two datasets. The LUCAS and LCDB datasets achieved overall accuracies of 95% (Poyry, 2014 as cited in Manderson et al., 2018) and 93.9% (Dunningham et al., 2000), respectively. However, these accuracy assessments were determined in earlier iterations, and likely, overall accuracies have since improved.

The LCDB version 5 (LCDBv5) is used in this study because it has an extensive suite of land surface categories (~33 on the mainland) and is frequently updated (~6 yearly intervals). It also has a higher thematic resolution and is more current (2018) than LUCAS's 2016. The land use classes in LUCAS were originally designated due to national circumstances (Whitehead et al. 2021). Since LUCAS is designed to address international reporting and accounting obligations related to agricultural and forestry activities, it has been deemed less reliable for urban trend analysis (Rutledge et al., 2010). Previously, the LCDB has been widely used to map national-scale indigenous or native forest cover (Cieraad et al., 2015; Dymond et al., 2017) for New Zealand. The LCDB integrates phenological information and other field-based ancillary data to provide more accurate estimations of grassland across the country (Julian et al., 2017). LULC categories representing areas of pastoral land and native forest were vital to this research.

The LCDBv5 was downloaded from the Land Resource Information System portal operated by Manaaki Whenua Landcare (available at https://lris.scinfo.org.nz/). The dataset is available in vector format, where land cover is represented by polygons, each delineating a specified area and corresponding to a distinct land cover. Each polygon within the dataset has an assigned set of attributes that describe the land cover for each of the time periods. The spatial resolution of the dataset is defined by the minimum mappable unit, which is one hectare (10,000 m^2). The land-cover categories of the LCDB were simplified and aggregated by land covers of similar or shared land use. The 35 LCDB(v5) categories were rationalised into eight, representing this study's most relevant land-use/land covers (Table 1).

The LULC classes in this study are rationalised as follows:

- *Horticulture/cropland* class is defined as agricultural land cultivated semi-annually or annually. Examples of this land use include orchards (avocados, kiwifruit, etc.), vineyards (e.g., grapes),

Table 1 Land-use / land-cover classification scheme adopted

Land use category	LCDBv5 land use sub-categories included
Cropland/horticulture	Short-rotation cropland, orchard, vineyard, and other perennial crop
Exotic forest	Exotic forest, harvested forest, deciduous hardwoods
Indigenous/native forest	Broadleaved indigenous hardwoods, indigenous forest
Other	Urban parkland/open space, sand, gravel, landslides, permanent snow and ice, herbaceous freshwater vegetation, herbaceous saline vegetation, mangroves, not land, surface mine or dumps
Pastoral land	Depleted grassland, high-producing exotic grassland, low-producing grassland, tall tussock grassland
Settlement/urban area	Built-up area, transport infrastructure
Shrubland/scrub	Alpine grass/herbfield, flaxland, fernland, gorse and broom, manuka and/or kanuka, Matagouri sub-alpine shrubland, mixed exotic shrubland, grey scrub
Waterbodies	Lake or pond, river, estuarine open water

and crops, such as strawberry fields, cereal crops, root crops, hops, and vegetable crops.

- *Exotic forest* class is defined as a land consisting of planted exotic forests, such as radiata pine (*Pinus radiata*) or Douglas Fir (*Pseudotsuga menziesii* (Mirbel) Franco), as well as land showing evidence of recent harvesting operations. This class also includes planted exotic deciduous hardwood species, such as elm (*Ulmus spp.*) and oak (*Quercus spp.*).
- *Native forest* class is defined as vegetation in advanced stages of secondary succession or mature indigenous forest consisting of tall forest canopy native podocarp or beech (*Nothofagus spp.*) species.
- *Pastoral land* class consists of land with varying fertility, managed extensively for wool or meat production, and land used less intensively but with a history of livestock grazing.
- *Settlement/urban area* class includes predominantly settlement areas and transport infrastructure, such as roads and railway lines.
- *Shrubland/scrub* class consists of single-species or mixed communities of small-to-medium-sized individuals (typically <3 m). This class includes communities of invasive plant species, such as gorse *(Ulex europaeus* L.) and broom (*Cytisus scoparius* (L.) Link). Early successional exotic and indigenous scrub communities are also included.
- *Other* class is land categories that were considered less important or could not be aggregated (see Table 1 for examples).

The modified-LCDB(v5) classes were then mapped over the study areas in four-time steps: summer 1996–1997, summer 2008–2009, summer 2012–2013, and summer 2018–2019, hereafter referred to as '1996', '2008', '2012', and '2018'.

Intensity analysis

Change detection was carried out for the following time intervals 1996–2008, 2008–2012, and 2012–2018. We performed three levels of intensity analysis: (1) time interval; (2) category analysis; and (3) transition analysis (Aldwaik and Pontius Jr, 2012). The interval level examines how the size of change during each time interval varies with respect to the duration of the intervals. The category level examines how the categories' gains and losses during an interval vary with respect to the sizes of those categories. The third level, transition, examines how the size of transitions during an interval varies with respect to the size of the categories available for these transitions. At each level, intensity analysis compares the observed changes to hypothetical uniform change, as indicated by a uniform line (Zhou et al., 2014). See supplementary material for detailed calculations for each level. Equations and mathematical notations are available at Villamor et al. (2014), whereas a free computer program is available at https://www2.clarku.edu/faculty/rpontius/. Pontius et al. (2013) further provided interpretations of the results. For this study, we only focused on the period of 2012–2018 to simplify results at the category (Section "Category analysis") and transition analyses level (Section "Transition analysis"). The unit of

measurement for each map reflects the change per hectare.

Furthermore, at each level of analysis, we also examine whether patterns will be stationary across time intervals. According to Zhou et al. (2014), stationarity for each level can be detected at (a) interval level: if the pattern of change in a one-time interval is the same as the pattern of change in a different time interval; (b) category level: stationarity means that the intensity of a category's gain is either greater than the uniform line for all intervals of less than the uniform line for all intervals; whereas, the intensity of a category's loss is either greater than the uniform line for all intervals or less than the uniform line for all intervals; and (c) transition from category *n* to category *m* is a *systematically targeting transition* when the gain of category *m* targets category *n*, while *m* targets the loss of *n;* whereas the transition from category *n* to category *m* is a systematically avoiding transition when the gain of *m* avoids *n*, while *m* avoids the loss of *n.* However, as we only use one-time interval (i.e., 2012–2018), we can only examine the stationarity at the interval level.

Results

Intensity analysis

The land-use categories (in percent) of each study site generated from the land-use maps for 1996, 2008, 2012, and 2018 are presented in Table 2. Overall, pastoral land represents the largest land category across the three study sites and time periods. In the Far North District, native forest was around 25% of the total land area, followed by shrubland (approx. 16%). In the Masterton District, the second biggest land category is exotic forest (18%), followed by native forests (10%). In Tararua District, almost 10% of the area is covered by native forest, followed by shrubland (6% of the total area). Using the recent two-time intervals, Fig. 2 shows the land-use maps of the three case studies and the maps of the gains and losses.

The speed of land-use changes in the three study areas is summarised in Fig. 3. During the period 2012–2018, the speed of land-use changes for the Far North and Masterton districts was far below the uniform intensity, which indicates that land-use change was slower than in the last two periods. The annual area of change during 1996–2008 is faster than during the two periods for both Far North District (Fig. 3a) and Masterton District (Fig. 3b), with intensities of 0.24% and 0.33%, respectively. In contrast, in the Tararua District, the annual area of change was the fastest during 2012–2018 (Fig. 3c). Nevertheless, both periods (e.g., 1996–2008 and 2008–2012) are below the uniform intensity of 0.18%.

Category analysis

At the category analysis level, which examines whether land-use categories are actively gaining or losing, the land-use change analysis during the period of 2012–2018 from all the case studies is presented in Fig. 4. Overall, two similar trends or patterns across the case studies were observed: (1) shrubland is actively losing, and (2) change in the native forest is *dormant*.

Table 2 The land area of key land uses and their changes between 1996 and 2018 (in percent)

	Far North district (%)				Masterton district (%)				Tararua district (%)			
	1996	2008	2012	2018	1996	2008	2012	2018	1996	2008	2012	2018
Native forest	24.8	24.7	24.8	24.8	10.0	9.9	9.9	9.9	9.7	9.7	9.7	9.7
Exotic forest	14.6	15.9	15.9	15.9	14.6	17.9	18.4	18.5	3.3	4.4	4.7	5.5
Horticultural/cropland	0.6	0.6	0.6	0.6	1.0	1.1	1.1	1.1	0.1	0.1	0.1	0.1
Pastoral land	40.4	39.1	39.1	39.2	65.2	62.1	61.9	61.9	79.4	78.1	78.1	77.8
Shrubland	16.0	16.0	15.9	15.8	7.9	7.6	7.4	7.3	6.8	6.9	6.7	6.3
Settlement area	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2
Others	2.8	2.7	2.7	2.7	0.6	0.6	0.6	0.6	0.3	0.3	0.3	0.3
Water bodies	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

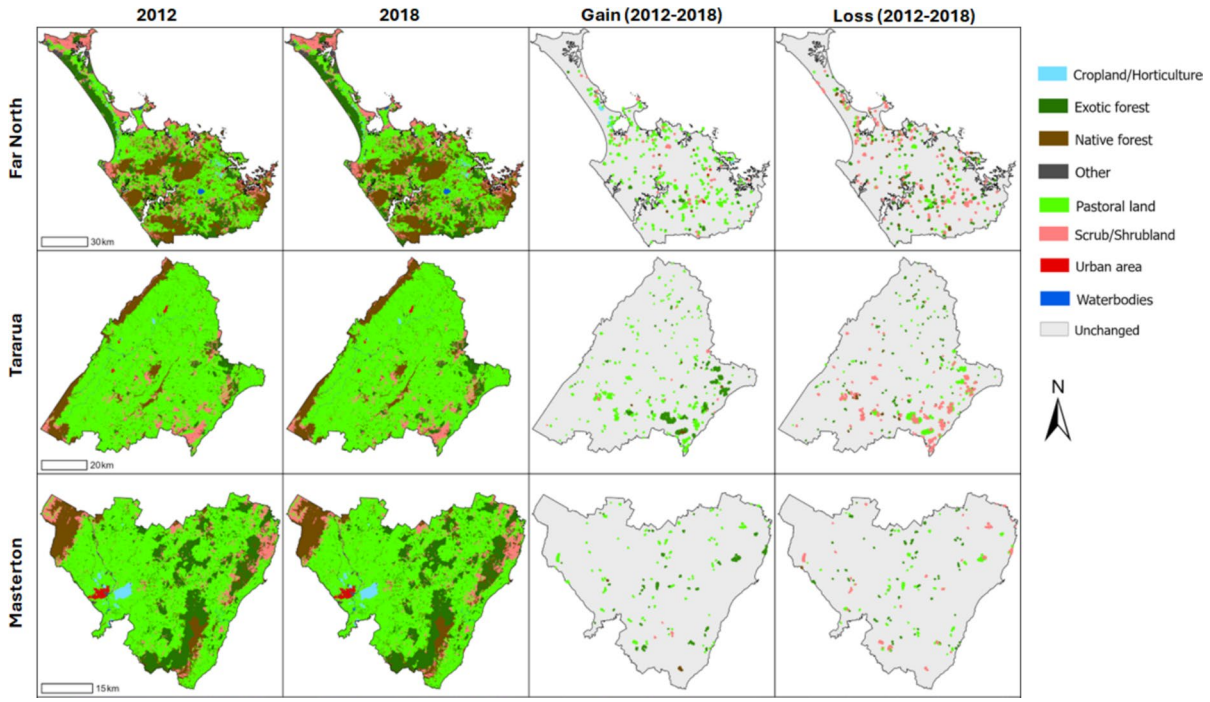


Fig. 2 Maps of the three case studies and the maps showing the gaining and losing of categories during the recent time interval (2012–2018)

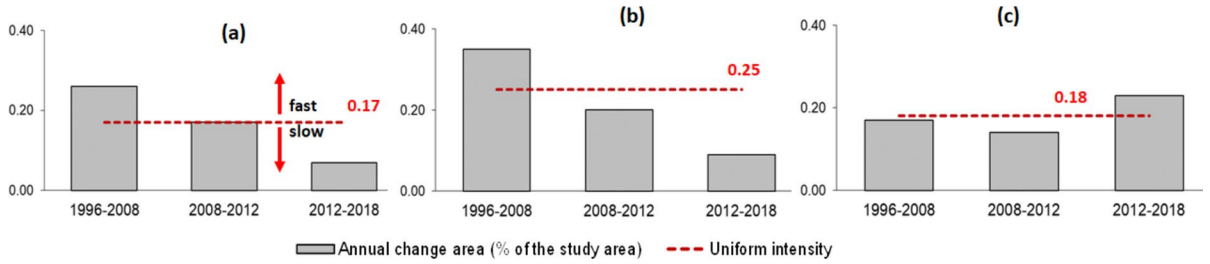


Fig. 3 Speed of land-use change in the (**a**) Far North district, **b** Masterton district, and (**c**) Tararua district

In the Far North District, the *actively gaining* land uses observed were horticulture/cropland, pastoral land, and others (e.g., parkland, open spaces, etc.), with annual change intensities of 1.41%, 0.10%, and 0.13%, respectively (Fig. 4a). In contrast, the land uses that were *actively losing* were shrubland and exotic forest, with annual change intensities of 0.17% and 0.10%, respectively. Exotic forest and shrubland were losing more than gaining.

In Masterton District (Fig. 4b), exotic forests were the only land use *actively gaining* and *losing*, with annual intensities of 0.23% and 0.11%, respectively. Shrubland was the land use *actively losing* three times more than exotic forests during 2012–2018.

In Tararua District (Fig. 4c), like the Masterton District, the exotic forest was the only land *actively gaining* and *losing* land use observed at an annual change intensity of 2.65% and 0.29%, respectively. In contrast, shrubland was *actively losing* land use at annual change intensities of 1.19%. Exotic forest is gaining more than losing.

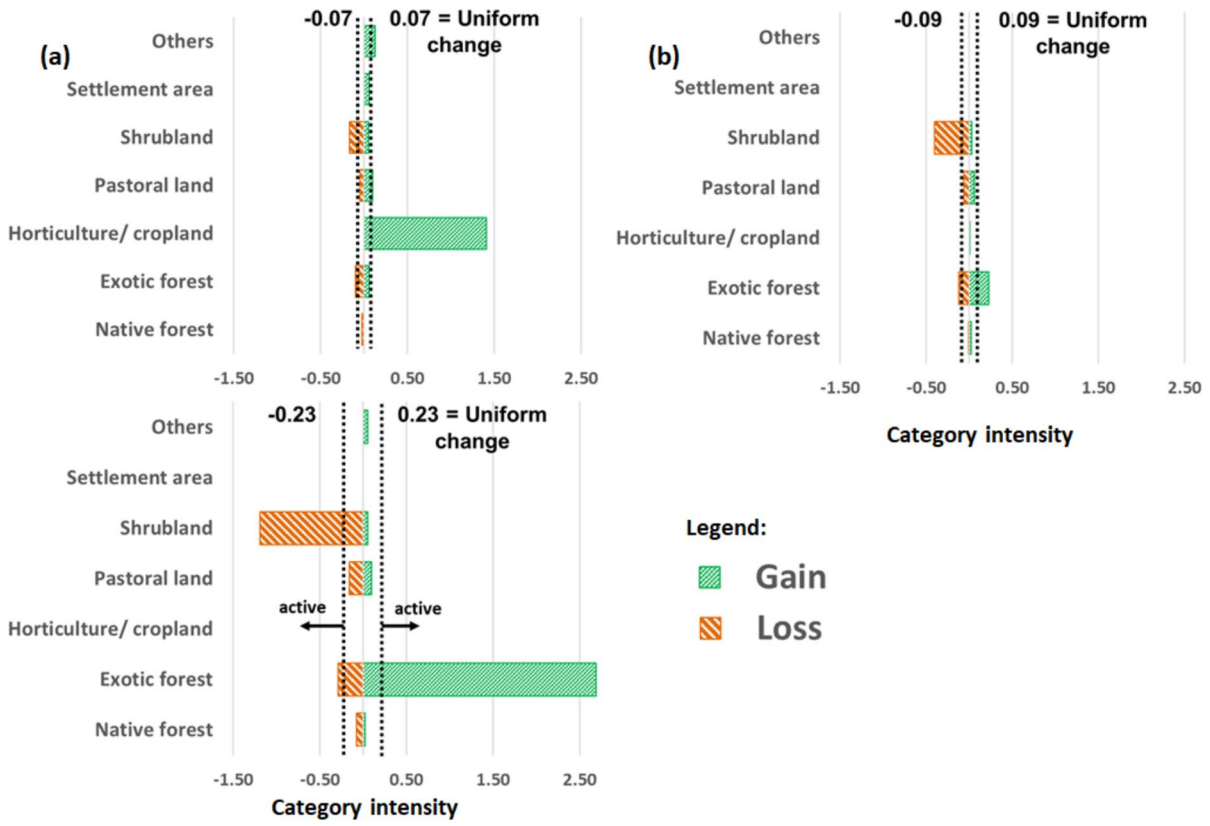


Fig. 4 Land-use intensity at the category level for (**a**) Far North district, **b** Masterton district, and **c** Tararua district for the recent period of 2012–2018

Transition analysis

This analysis determines which land uses are actively targeted or avoided. We presented the pattern of transition per case study.

Far north district

Figure 5 shows the active land uses during 2012–2018 targeted for exotic forests and pastoral land. For the gain of exotic forests, the actively targeted land use is

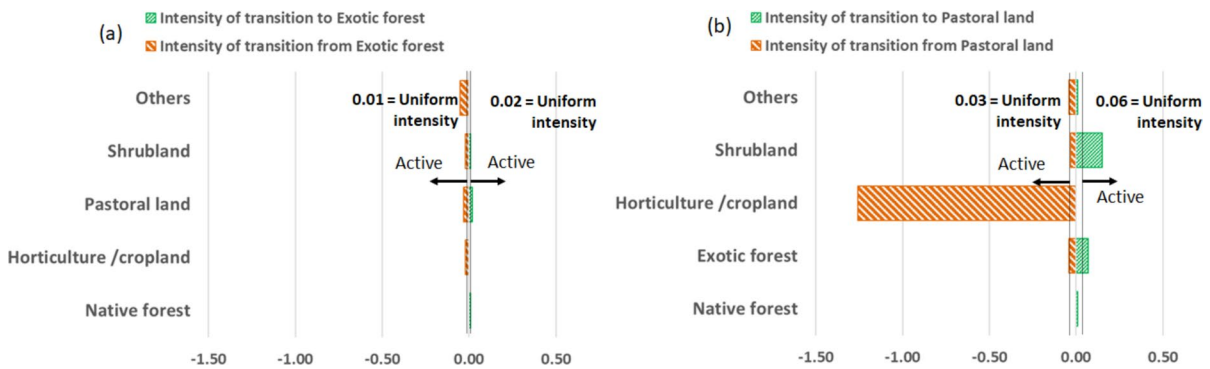


Fig. 5 Transition level intensities for Exotic Forest (**a**) and Pastoral land (**b**) during 2012–2018 in Far North District

the pastoral land with intensity the same as the uniform intensity of 0.02% (Fig. 5a). In contrast, the loss of exotic forest was actively targeted for the transition to horticulture/cropland, pastoral land, shrubland and others at the intensities of 0.02%, 0.03%, 0.02% and 0.05%, respectively. This suggests exotic forests were losing more to most land uses (particularly to others). For pastoral land, Fig. 5b shows that exotic forests (at an intensity of 0.07%) and shrublands (at an intensity of 0.15%) were actively targeted for the transition to pastoral land. In contrast, horticulture/cropland, exotic forest, shrubland and others (e.g., settlement) actively targeted pastoral land with an intensity of 1.26%, 0.04%, 0.03% and 0.04%, respectively. The transition to horticulture from pastoral land was the greatest. These results suggest that horticulture/cropland was the most active land use in transitioning from pastoral land.

Masterton district

In the Masterton district, exotic forest and pastoral land were the most active land uses observed during 2012–2018 (Fig. 6). In Fig. 6a, pastoral land and shrubland were actively targeted by exotic forest at intensities of 0.05% and 0.12%, respectively. The transition from shrubland to exotic forest is greater than that of pastoral land. In contrast, pastoral land actively targeted exotic forest. In Fig. 6b, shrubland and exotic forests were actively targeted by pastoral land at intensities of 0.25% and 0.11%, respectively. The transition from shrubland to pastoral land is greater than that of exotic forests. In contrast, pastoral land is actively targeted by exotic forest at an intensity of 0.18%.

These results suggest that both exotic forest and pastoral land are targeting shrubland. For this reason, shrubland was actively losing (as presented in Section "Results". Category analysis).

Tararua district

Exotic forests were the most active land use observed in the Tararua District. Figure 7a shows that exotic forests actively targeted pastoral land and shrubland during 2012–2018 at an intensity of 0.15% and 0.23%, respectively. However, none of the land uses were transitioning from exotic forests. In Fig. 7b, pastoral land actively targeted only shrubland at an intensity of 0.82%. In contrast, exotic forests actively targeted pastoral land at an intensity of 2.22%.

These results suggest two patterns of transitions during 2012–2018: (1) exotic forest targeted mostly the pastoral land and shrubland, while (2) pastoral land targeted mainly the shrubland.

Discussion

Which time intervals show a relatively *slow* or *fast* annual change in area?

The period of 2012–2018 was observed to be the slowest in annual area change among the three-time intervals used for the two case study sites, except Tararua district. This slow land-use change pattern has also been observed by Kerr and Olssen

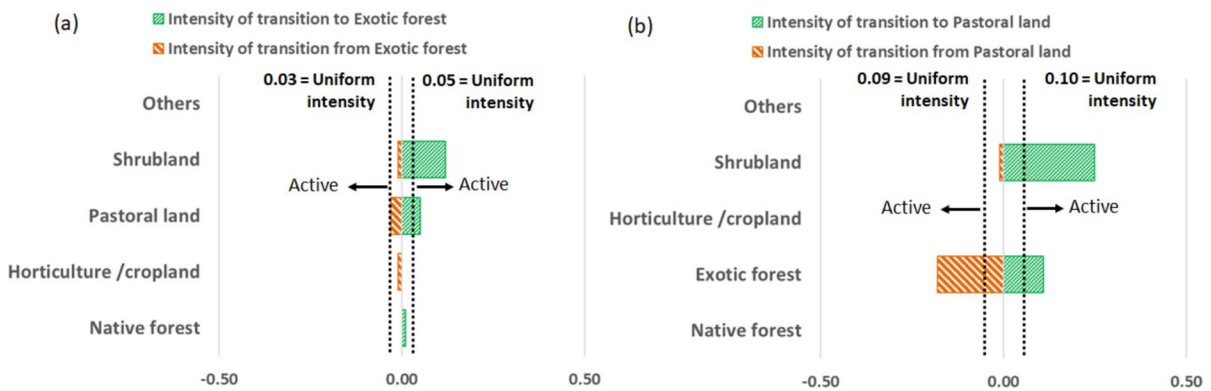


Fig. 6 Transition level intensities for Exotic Forest (**a**) and Pastoral land (**b**) during 2012–2018 in Masterton District

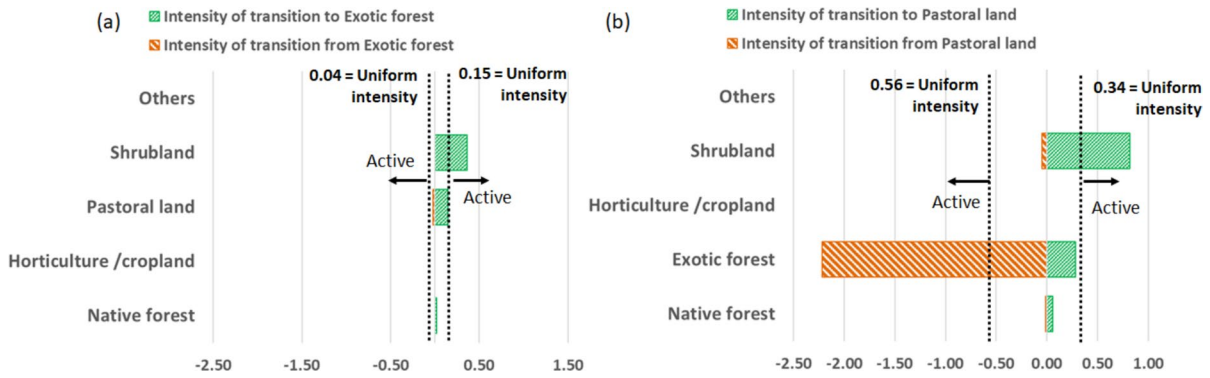


Fig. 7 Transition level intensities for exotic forest (**a**) and Pastoral land (**b**) during 2012–2018 in Tararua district

(2012). The slow pattern of annual area change can be attributed to the two critical pieces of legislation that control land-use change in the country, namely, the Resource Management Act, 1991 (RMA) (and amendments) and the Exclusive Economic Zone and Continental Shelf (Environmental Effects) Act, 2012 (EEZ) (Carter, 2018). Other cross-cutting policies that influence current land use include the National Policy Statement for Highly Productive Land, which protects land-based primary production from inappropriate use and development, and the National Environmental Standards for Freshwater. These regulations, mainly RMA, were observed to be a limiting factor in landowners' current land-use practices. In a study conducted by Renwick et al. (2022), it was noted that regulations increasingly influence land managers. They view these regulations as a force driving them to transition to high-value and intensified systems. Nevertheless, the profitability of alternative land uses remains a motivation to change land managers from current practices (Renwick et al., 2022).

However, the period 2012–2018 in Tararua District was observed to be the fastest among the other time intervals. The transition was largely due to the increase in exotic forests in the area, as forest growers began planting woodlots of *P. radiata*, *P. menziesii*, *Eucalyptus* sp., *Cupressus* sp., and other exotic tree species (Gordon & Hocking, 2008).

Which land categories are relatively *dormant* compared to those *active* during a given time interval?

Based on category analysis during the period 2012–2018 (Fig. 4), the native forest was consistently dormant across the three case study sites. This can again be attributed to the RMA policy, which extends statutory functions for protecting and maintaining indigenous vegetation on private land to local authorities. Furthermore, these native forests are owned by the Crown (government) and are mostly protected in national parks, scenic reserves, and conservation areas. The Department of Conservation manages the native forests for biodiversity conservation, heritage and recreation (MPI, 2022).

Despite the slow transition, transitions occurred for shrubland, pastoral and exotic forests. This observation corroborates the study of Whitehead et al. (2021), which noted that between 2002 and 2019, a decrease in the area for agriculture was observed mainly due to the conversion of grassland (in this study, pastoral land) to forestry. Unique among the case studies in the research, horticulture/cropland in the Far North was observed to be actively in transition.

Which transitions are being *targeted* and which are being *avoided* during a given time interval?

The transition analysis of three case studies from 2012 to 2018 showed that native forest was the only land use consistently avoided among exotic forest, horticultural, pastoral land, and shrubland. However, each case study observed slightly different transition patterns for the same period.

In the Far North district, horticulture/cropland was the most active land use, mainly targeting pastoral land and exotic forests. Avocado is the main horticultural crop in the Far North District because it offers highly favourable growing conditions. The expansion of avocado orchards in the Far North District is mainly due to global export demand (predominantly to Australia) and consumer trends (e.g., the paleo diet and the explosion of Mexican food popularity). In 2019, avocados were the fifth largest horticultural export of New Zealand, generating $104 million in export revenues (MPI, 2019). The growing global demand for avocados is expected to result in further changes in land use in the Far North area. Additionally, due to increasing labour shortages in dairy farming, embracing technology in the horticultural industry would reduce their vulnerability to labour shortages (Renwick et al., 2022). However, a life-cycle analysis study conducted by Majumdar and McLaren (2024) found that fertiliser use and soil conditioner use contributed most to the impact of eutrophication on the Far North's freshwater and freshwater ecotoxicity. The same study calculated that the water use impact score for the orchard stage was 0.75 m^3 world equivalent/kg avocados, the highest among the case studies in New Zealand. However, no studies use the same method to compare the water use and eutrophication impact of exotic forests and pastoral land to determine which land use is more environmentally friendly. On the other hand, indicative nitrogen leaching from different land uses (e.g., dairy, sheep and beef, horticultural crops, and forestry) is available in the Ministry of Primary Industry's Land Use Change Report 2017, reporting that dairy and intensive vegetable farming has the greatest nitrogen leaching potential (MPI, 2017).

In the Masterton district, like in the Tararua district, exotic forest and pastoral land were the most active land uses, and both targeted shrubland. Because many of these lands were marginal for primary production and erosion-prone areas, a large number of properties have been converted to forestry or conservation woodlots (Cameron, 2016). However, the land-use transition is greater in converting shrubland to pastoral land than in converting shrubland to exotic forest (Fig. 7). From a greenhouse gasses emission viewpoint, there is a significant reduction if shrubland is converted to exotic forests rather than to pastoral land (MPI, 2017). Also, vegetation clearance to provide pasture on hill country has resulted in increased erosion in the area, which in turn affects the water quality of the rivers (Stewart, 2014). In eroding pasture land, poplar and willow poles were planted (Cameron, 2016). In retired lands from grazing, *P. radiata* woodlots were planted for farm conservation. *Leptospermum scoparium* (J.R.Forst. & G.Forst, mānuka) and *Kunzea ericoides* ((A.Rich.) Joy Thomps., kānuka) trees for honey production were used to increase slope stability by changing the regime of soil moisture. On the other hand, during the last 20–30 years, the Wairarapa region, which includes the Masterton district, experienced a loss of hill country pastoral lands to exotic forests (Falloon, 2015).

In the Tararua District, exotic forest and pastoral land were the most active land uses. Still, exotic forests mainly targeted the shrubland rather than pastoral land, while pastoral land targeted mainly the shrubland. The council's 2021 report stated that in 2019, $NZ 110 million worth of pastoral land was sold, with 31% of the sold land converted to carbon farming (a term which describes the planting of trees for carbon sequestration and selling carbon credits without the intention of harvest), 25% for forestry, and only 37% strictly for pastoral use (Tararua District Council, 2021b). In the same report, aside from several freshwater policies, the increase in exotic forests in the district was due to greenhouse gas-related legislation. Accordingly, it is more profitable to seek carbon sequestration opportunities rather than reduce production to meet the greenhouse gasses targets. This may suggest the transition of most exotic forests from pastoral land (Fig. 7b). However, the Tararua District Council sees exotic forest carbon farming (as opposed to rotational forestry) as a significant loss to the district because the income is only coming from carbon credits with no locally generated jobs (Tararua District Council, 2021a). This presents an issue regarding large portions of

land from the district being converted into carbon farms, reducing employment and land value (Collins & McFetridge, 2021; Harper, 2019). Farmers also express worry towards productive land being wasted due to carbon farming conversion into *P. radiata*. Some share the belief that eventually, *P. radiata* may no longer be worth the same once plantations are old enough to harvest (Harper, 2019), hence the scepticism of land value.

Potential implications and limitations

Results from the three levels of analyses for the three case studies provided evidence that there were changes in land-use categories not captured by only using the overall net land-use changes presented in Table 1. Analyses based on net changes may fail to reveal the total change in the landscape (Yuan et al., 2016). This is because a zero net change does not necessarily imply a lack of change (Mwangi et al., 2017). There is a possibility that a change occurs in such a way that the location of a land category changes between time one and time two while the quantity (size) remains the same (Pontius et al., 2004). According to Mwangi et al. (2017) revealing this kind of information is essential for conservation and management because the changes may have affected hydrological catchment properties, such as infiltration, soil/slope water pathways and related erosion/ water quality patterns.

Our case studies indicate a minimal decrease in native forests, thus providing insight into deforestation at the local level. Instead, deforestation (defined in the NZ context as the decision not to replant following harvesting with the conversion to another land use) occurred mainly in exotic forests, where some areas are converted to horticulture (e.g., Far North District) and pastoral land (e.g., Far North and Masterton Districts) during the period 2008–2018. Studies that rely on tree cover loss and use vague definitions of tree cover or forest, such as a 30% tree canopy (Hansen et al., 2010), may incorrectly categorise both native and exotic forests as part of the tree cover. This could result in an overestimation of deforestation or tree cover loss when exotic forest harvesting takes place. According to the Marrakesh Accord,[1] deforestation excludes forest harvested and replanted and harvested forests that are not replanted by naturally regenerating back into forests. Furthermore, the Climate Change Response Act of 2002[2] (Section 179) identifies deforestation if specified stocking has not been achieved within four years of clearing by replanting or regeneration or a specified canopy has not been achieved within ten years of clearing. From this angle, local-scale studies of land-use change are necessary to validate global and regional tree cover loss assessments for measuring deforestation rates.

Furthermore, the intensity analysis results provide insights into the implications of human influence on land-use patterns at the local level. Earlier studies of land-use changes in New Zealand were mainly driven by economic factors (Dorner & Hyslop, 2014; Kerr & Olssen, 2012). Our findings suggest that land uses in rural areas are driven by a combination of economic incentives, regulatory frameworks, and societal demands for resources, showcasing a complex interplay of anthropogenic and climate pressures. One of the most notable human influences on land use is the agriculture-related demand for pastoral and horticultural systems. In Masterton and Tararua districts, pastoral land was shown to actively transition to exotic forests, demonstrating a shift in landowner preferences. This shift can often stem from the pursuit of higher economic returns, or the pressures exerted by market demand for timber and related products (e.g., carbon credits from emission trading schemes). The transition highlights a strategic response to economic conditions, where landowners are adapting their practices to maximise profitability. This tendency is further supported by Renwick et al. (2022), noting that ongoing profitability remains a crucial motivation for land use alterations in New Zealand. In addition to economic factors, regulatory frameworks such as the Resource Management Act (RMA) and environmental policies have played a defined role in shaping land-use changes. While the RMA serves to protect certain areas from conversion, it can inadvertently limit land management flexibility, compelling landowners to seek alternative uses that comply with legislative mandates while also aiming for economic viability. This dual influence creates a landscape where decision-making is not solely based

[1] https://unfccc.int/cop7/documents/accords_draft.pdf

[2] https://www.legislation.govt.nz/act/public/2002/0040/latest/DLM158584.html

on the land's natural characteristics but is heavily informed by surrounding policies, thus impacting the pace and nature of transitions. The finding that native forests remained dormant during the study period can be attributed to legal protections that regulate the use of indigenous vegetation. These policies are essential for biodiversity conservation but also limit the potential transitions that could occur in response to human activities. As seen in the study, while areas such as shrubland and exotic forests are actively transitioning, native forests stand largely untouched, underscoring the human restraint imposed by both conservation and economic priorities. Interestingly, the Tararua District experienced a rapid rise in exotic forest areas during the same period, primarily due to tree planting initiatives targeted by forest growers. This phenomenon indicates not just a market-driven response but also highlights a commitment to land use that builds on climate change mitigation strategies, where afforestation is seen as a beneficial response to environmental challenges.

One limitation of this study is that we utilised only three case studies or districts. More cases are needed to robustly understand the transition process at the local level and determine the local-scale factors affecting transition and deforestation. Also, land-use intensity analysis was used to detect the changes in land use in detail, but the impacts of these changes on ecological structure and functions of land use, such as native and exotic forests, still need to be further investigated using other analytical tools. There are also limitations of the Geographic Information System (GIS) data. While the accuracy of the LCDB has been validated using ground-truth data, stakeholder input, aerial photographs, and manual correction of the polygon boundaries (Dymond et al., 2017), the dataset is primarily based on satellite data with a 10–30 m spatial resolution. Due to the low resolution of the underlying imagery, small-scale changes in land cover cannot be reliably detected. Additionally, as the original 33 mainland land classes of the LCDB are aggregated into broader classes, the coarse nature of the classes used in this study may obscure the influence of the finer-scale classes on the results. Furthermore, intensity analysis as an accounting framework relies on the transition matrices. However, its ability to map the speed of change at the interval level to further identify patterns remains limited. For future work, the suggestion of mapping the incidents, states and combinations as proposed by Pontius et al. (2017) could address this limitation.

Conclusions

This study applies the intensity analysis to examine the patterns, dynamics and processes of land-use change or transition in the three selected rural landscapes of New Zealand in three consecutive time intervals between 1996 and 2018. During the period 2012–2018, land-use transition slowed down in all case studies except Tararua District, and changes in native forests were dormant. These observations convey a positive message regarding the country's conservation efforts and related policies towards that objective. These remaining native forests in New Zealand serve as the refuge for its unique and diverse flora and fauna. On the other hand, most of the active transitions occurred in exotic forests, pasture lands and shrublands.

The changes and trends identified in the category and transition levels provided valuable insights into the specific patterns and factors that are driving change in the three case studies. For example, in the Far North District, horticulture emerged as a significant land use not observed in the other two districts. The intensity analysis approach helps examine the underlying reasons for these observed patterns. It is recommended that these land-use patterns be compared with those at the national level. This will enable us to effectively address and manage the impacts of land-use changes and prevent discrepancies between local case studies and the national-level understanding of land-use changes.

The results of our study underline the increasingly complex nature of land-use dynamics, where human influence—through economic, policy, and environmental lenses—directly dictates the transitions within landscapes. The resulting shifts reflect a balance or tension between conservation needs, economic aspirations, and the sustainability of land resources.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval No human participants, plants, or animals were used in this study.

Consent to publish This paper has undergone a process of approval to publish.

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