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RESEARCH ARTICLE

Forests from the grass: natural regeneration of woody vegetation in temperate marginal hill farmland under minimum interference management

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Marginal hill farmland is a key target for the restoration of temperate indigenous forest, which can help mitigate climate change and biodiversity loss. Reliance on natural regeneration and minimum interference management (MIM) is a low-cost restoration strategy for farmers, with the transition from pasture to woody scrub vegetation (whether indigenous or exotic) an important early successional phase. However, few studies have determined the key factors that influence the regeneration of woody vegetation on pastoral farmland, nor the rate at which regeneration occurs. Using a geospatial analysis of a New Zealand pastoral hill farm subject to variable grazing and MIM, this study found that only 3.8% of grassland experienced detectable regeneration of woody vegetation over 16 years. The key factor influencing natural regeneration was proximity to existing woody vegetation, with the probability of regeneration decreasing as distance increased. Cattle grazing had a significant negative impact, with regeneration more likely to occur in areas free from cattle. Sheep grazing exhibited no significant positive or negative relationship with regeneration. To support natural regeneration of woody vegetation, landowners should prioritize areas with a higher presence of existing woody vegetation and exclude cattle. To increase the rate of regeneration, landowners should consider active management regimes and supplemental restoration strategies, such as applied nucleation and the introduction of nurse species. Given the increased cost and complexity of such approaches, effective government incentive programmes may be needed to provide landowners with financial support and expertise.

Key words: environmental factors, hill country, pastoral farmland, remote sensing, restoration, temperate forest

Implications for Practice

- Owners of temperate marginal hill farmland dominated by pasture are likely to experience a slow rate of natural regeneration of woody vegetation if relying on minimum interference management with continued mammalian browsing.
- To maximize natural regeneration, owners should prioritize locations adjacent to existing woody vegetation and exclude cattle grazing, particularly from areas with high woody vegetation coverage.
- For faster regeneration rates, active regeneration strategies and management regimes should be considered, such as applied nucleation of woody vegetation, the introduction of nurse species, and the complete exclusion of browsers.
- Given the higher cost and complexity of such approaches, governments may need to provide landowners with increased financial support and expertise to achieve national and global restoration objectives.

Introduction

Agriculture and human settlement over hundreds of years have resulted in widespread clearance of temperate forests (Currie & Bergen 2008; Gilliam 2016). For example, in New Zealand approximately three quarters of the original temperate forest cover has been destroyed since human arrival (Fleet 1986; Ewers et al. 2006). Temperate forest clearance has had significant negative impacts, including biodiversity loss, reduced carbon storage, and degradation of soil and water resources (Foley et al. 2005). Many organizations internationally have developed restoration targets, such as the IUCN Bonn Challenge goal of restoring 350 million hectares of forest by 2030 (Crouzeilles et al. 2020). Individual countries have also developed national goals. For example, the New Zealand Climate Change Commission has recommended establishing 300,000 ha of permanent indigenous forest in New Zealand by 2035 as a carbon sink and critical habitat for indigenous flora and fauna (He Pou a Rangi Climate Change Commission 2021).

Marginal hill farmland (referred to as hill country in New Zealand) is an attractive location for restoration due to its

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low value for pastoral farming, with many hill country farmers interested in alternative uses for their land (Bergin & Kimberley 2014; Peart & Woodhouse 2021). Hill farmland is characterized by steep slopes above 15° and an altitude below 1,000 m above sea level (Cameron 2016), with the land considered marginal where there are severe constraints on its use for farming due to factors such as erosion and climate (Kang et al. 2013; Shahid & Al-Shankiti 2013). In New Zealand, there is an estimated 2.8 million hectares of marginal hill farmland that could support tree species, with financial incentives and carbon credits available to landowners for restoring their land to forest (Chartres et al. 2020). The restoration of permanent forest on marginal hill farmland can also provide additional environmental benefits, including reduced soil erosion and improved water quality (Davis et al. 2009; Di Sacco et al. 2021).

Restoring forest on marginal hill farmland is challenging due to its biophysical characteristics, with the land often steep, erosion prone, and difficult to access (Davis et al. 2009). This makes conventional restoration techniques, such as planting nursery raised seedlings, difficult and costly, with some studies estimating a cost of up to US$34,000 per hectare (Catterall & Harrison 2006; Carswell et al. 2012). In New Zealand, direct seeding is not commonly used due to the unavailability of indigenous seeds, unreliable germination, and intensive competition from exotic grasses (Douglas et al. 2007). A lower cost and potentially more suitable alternative is natural regeneration, which relies on spontaneous dispersal of remnant indigenous woody vegetation to recolonise deforested land through a gradual successional process (Chazdon 2017; Wilson et al. 2017). In addition to cost efficiencies, natural regeneration results in improved biodiversity outcomes relative to other techniques, including higher abundance and species richness for indigenous plants, birds, and invertebrates (Crouzeilles et al. 2017).

Natural regeneration is an opportunistic and unpredictable process (Chazdon & Guariguata 2016), with substantial uncertainty regarding where and when regeneration will occur (Crouzeilles et al. 2020), particularly on temperate marginal hill farmland. Existing studies of natural regeneration on temperate farmland focus on specific tree species (Vesk & Dorrough 2006; Bergin & Kimberley 2014), not the initial transition from pasture to woody scrub vegetation. In open hill country, many indigenous tree seedlings struggle to germinate and survive due to harsh microclimates and the suppressive effect of pasture grasses (Reay & Norton 1999; Miller & Wells 2003; Ledgard & Davis 2004). Early successional nurse species (either indigenous or exotic) are often needed to limit grass growth, reduce abiotic stress, and provide protection from browsers to support seedling establishment (Wilson 1994; Padilla & Pugnaire 2006; Tulod & Norton 2020). This initial regeneration of woody vegetation from pasture is therefore a critical successional phase that determines long-term restoration success, but which remains poorly understood.

Livestock grazing is generally considered to be detrimental to the long-term natural regeneration of temperate forests (Smale et al. 2008; Carmona et al. 2013). However, little is known about whether short term low intensity grazing may be beneficial for alleviating woody vegetation competition from exotic grasses and supporting the early establishment of less palatable woody vegetation in grassland (Davis & Meurk 2001; Bergin & Kimberley 2014). This is an important consideration for farmers seeking to maintain a productive use of hill farmland, particularly given the slow speed at which natural regeneration can occur. Reay and Norton (1999) noted the slow colonization of grassland by forest plants on a 0.5 ha study site in temperate hill country. However, we are not aware of any studies that quantify the rate of change across an entire temperate hill farm property. This is important information for landowners, as a slow rate of change is often incompatible with government financial incentive schemes and may result in landowners prematurely terminating their restoration projects (Zahawi et al. 2014). For hill country farmers with limited resources, these uncertainties create financial risk, which can act as a significant barrier to natural regeneration projects (Vesk & Dorrough 2006; Funk 2009).

This study addresses the current knowledge gaps through a geospatial case study of a temperate hill country farm in New Zealand under minimum interference management (MIM). The key questions this study answers relate to the rate of natural regeneration of woody vegetation in temperate grassland, the influence of various abiotic environmental factors, and the effect of livestock grazing. The findings will help landowners set realistic expectations for natural regeneration under typical hill farm conditions and enable the development of more effective and targeted strategies for restoring temperate forests in pastoral landscapes.

Methods

The method used in this paper involved two sequential stages, as illustrated in Figure 1. Stage 1 utilized high-resolution aerial imagery to identify areas of natural regeneration of woody vegetation, with Stage 2 comparing those areas with a range of spatial variables to evaluate the factors that may influence natural regeneration. This fine scale geospatial method can be applied to other pastoral locations to identify and evaluate changes in woody vegetation over time at the property scale.

Study Site

The study site is Oashore Station, which is a hill farm of approximately 540 ha located on the southern coast of Banks Peninsula (Te Pātaka o Rākaihautū) in Canterbury, New Zealand (Fig. 2). The site is characterized by steep slopes on the sides of the valleys (>15°) and flatter land on the ridge tops, with elevation ranging from sea level to approximately 450 m a.sl. The climate is cool temperate, oceanic and subhumid, with site conditions following the general altitudinal gradient on Banks Peninsula of colder temperatures and higher rainfall at higher elevations (Whyte 2002; Wilson 2003). Although Banks Peninsula was historically covered in forest (Wilson 1994; Peart & Woodhouse 2021), the site has a long history of human occupation and has been actively farmed for sheep and cattle production since the mid-1800s (Whyte 2002). As a consequence, the site is now dominated by exotic pasture grasses (such as cocksfoot [*Dactylis glomerata*] and perennial ryegrass [*Lolium perenne*])

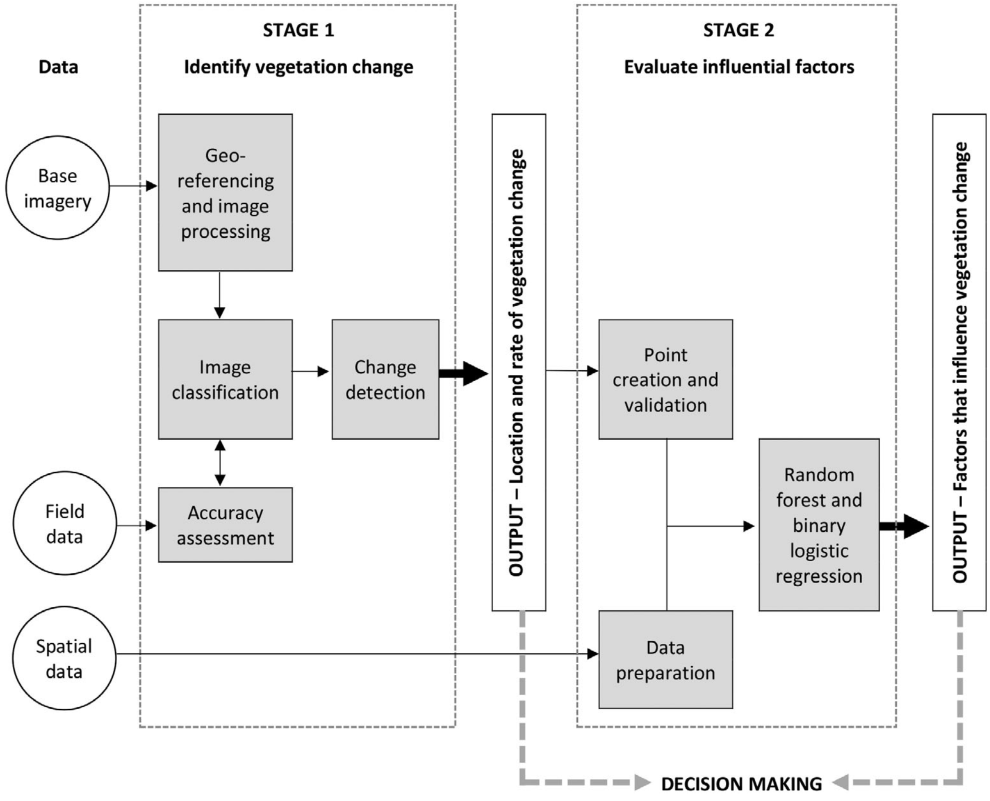

Figure 1. Diagrammatic summary of two sequential stages in the method: identification of vegetation change (Stage 1) and evaluation of factors that influence change (Stage 2).

with only remnants of indigenous vegetation, including tussock grassland, indigenous scrub and shrubland, and some podocarp-broadleaved forest in stream gullies (Whyte 2002).

The site is managed in accordance with an ecological restoration plan developed in 2002 that seeks to restore self-sustaining indigenous ecosystems through reliance on natural regeneration (Whyte 2002). This restoration plan is based on the concept of MIM, which involves removing the most obvious impediments to natural regeneration and allowing nature to do the rest (Wilson 1994). MIM typically involves the complete exclusion of livestock due to the significant negative impact of grazing on palatable regenerating seedlings (Wilson 1994; Smale et al. 2008). However, due to the high coverage of pasture, grazing by cattle and sheep has been allowed to continue in some areas to try and alleviate competition from exotic grasses and support the establishment of browse-tolerant woody species (Whyte 2002). This has resulted in a variable grazing regime where different areas of the site have been fenced to exclude cattle and/or sheep for different lengths of time, as illustrated in Figure 3. Other management actions undertaken on the site to support natural regeneration include the trapping and shooting of introduced mammalian browsers, particularly possums and feral goats.

The site was selected as a case study because it has typical characteristics of marginal hill farmland, including varied topography and a dominance of exotic pasture grasses, with all of the site classified as marginal land for pastoral farming (category 6 and 7 land under the New Zealand Land Resource Inventory) (Newsome et al. 2008). The long-term management of the site for natural regeneration has also resulted in observable changes in woody vegetation, which can be compared with a wide variation of environmental conditions and grazing regimes to evaluate their potential influence on natural regeneration.

Stage 1—Identification of Natural Regeneration

To identify locations where natural regeneration had occurred, high-resolution aerial images (RGB, 0.25 m) were extracted from Google Earth Pro for two dates in summer, 16 years apart (January 2003 and January 2019). The two aerial images were georeferenced using 418 control points, with a spline transformation applied to ensure accurate spatial alignment (RMSE 0.03 m). A convolution filter was applied to sharpen the images and improve differentiation of features, with each image clipped to the site boundary to simplify the image classification process.

Supervised object-based image classification was then carried out using the random forest classifier (Breiman 2001) to convert each image into classified land cover maps, with two land cover classes of "grassland" and "woody vegetation". A total of 72 training sample polygons were created, with 36 for each land cover class. A wide variety of parameters were trialed for each step of the image classification process, with the output being

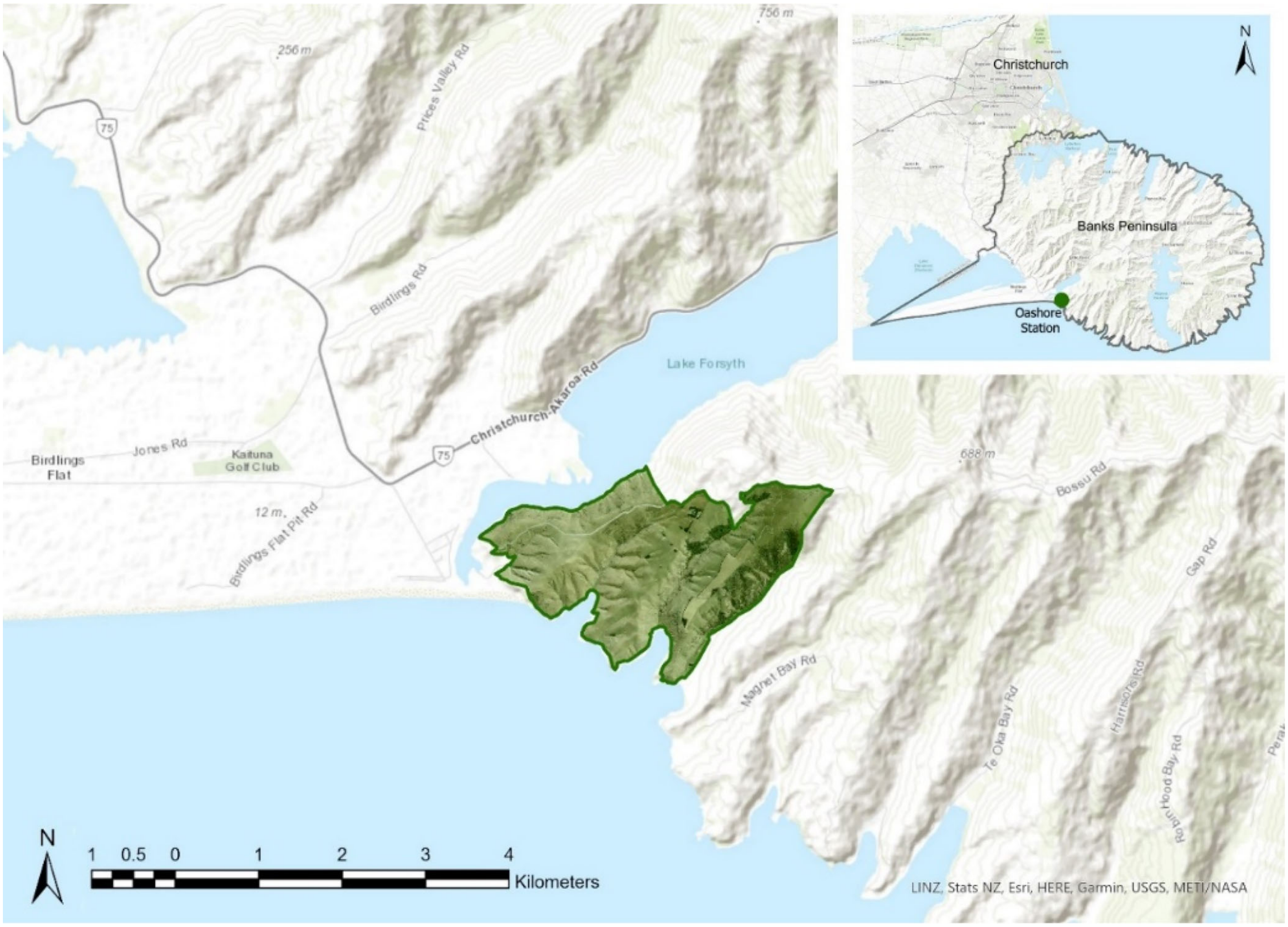

Figure 2. Location of Oashore Station on Banks Peninsula, Canterbury, New Zealand.

two classified rasters at 0.25 m resolution showing the distribution of grassland and woody vegetation across the site in 2003 and 2019. An accuracy assessment was completed for the classified land cover maps based on a visual interpretation of aerial imagery and actual ground truth data gathered during site visits for 100 points across the study area. The overall accuracy for each image classification was high, which was reflected in overall accuracy and Kappa index values of 95% and 0.89 (2013 image) and 92% and 0.84 (2019 image). However, there were several Type 1 (false positive) errors for the areas classified as

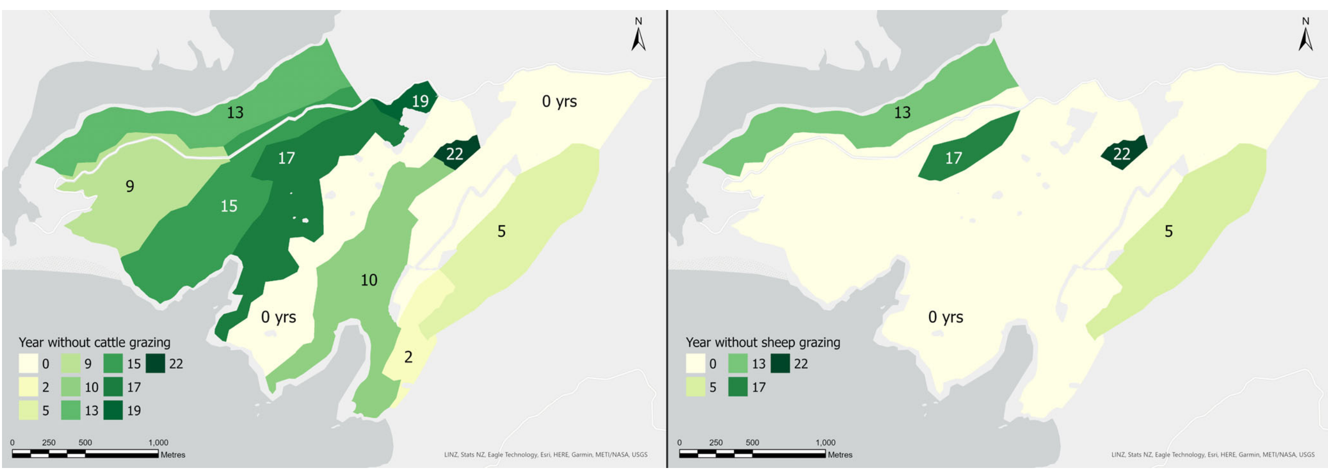

Figure 3. Location of areas within Oashore Station that have been free from grazing by cattle (left) and sheep (right) for different periods of time.

"grassland" in both images, which indicates that the process may have underrepresented the presence of woody vegetation.

To ensure that only natural regeneration was detected, anthropogenic elements such as buildings, roads, and exotic shelter belts were clipped from the classified images (Carmel & Kadmon 1999). The classified land cover maps were then compared to create a change detection raster that identified those areas that had changed from grassland in 2003 to woody vegetation in 2019, as presented in the results. Changes in the opposite direction (from woody vegetation to grassland) were not assessed and the species or age of detected woody vegetation was not identified due to the absence of a detailed site survey. Figure 4 illustrates the application of the method to part of the site to show how high-resolution imagery was converted into classified land-cover maps, which were then compared to identify areas of regeneration. The creation of a change detection raster for the entire site enabled quantification of the total amount of regeneration and calculation of the rate of change over time.

Stage 2—Evaluation of Factors that Influenced Regeneration

To evaluate the factors that influenced the observed changes, the change detection raster was converted into polygons and then into a series of sample points across the site using the Create Random Points tool in ArcGIS Pro v2.8.3 (Environmental Systems Research Institute, Redlands, CA, U.S.A.). A total of 400 random points were initially created across the study site, with a minimum separation distance of 50 m and an even number of points in each class. These points were subjected to a visual validation process, which involved manually comparing the point location to the underlying change detection raster and base imagery to ensure that it represented a point of actual change. This process detected errors in approximately 25% of the initial sample points, which were primarily due to minor misalignments between the two images. Where obvious errors were detected, those points were modified and/or deleted from the analysis. Additional points were then manually added or removed to achieve a total sample size of 300 visually validated points, including 150 points of "regeneration" and 150 points of "no regeneration."

Spatial data were obtained at 1 m resolution for a range of potential explanatory variables, including slope, elevation, aspect, solar radiation, and topographical wetness, all of which were derived from a high-resolution digital elevation model (Canterbury-Banks Peninsula 1 m DEM [2018–2019] sourced from the Land Information New Zealand Data Service). All such variables had continuous values, except for aspect which was reclassified into northeast (0°–90°), southeast (90°–180°), southwest (180°–270°), and northwest (270°–360°). This was complemented by data on the proximity of existing woody vegetation (from the image classification process), including distance to the nearest woody vegetation and the percentage of woody vegetation within a 25 m radius. The number of years that cattle and/or sheep grazing had been excluded for different parts of the site was obtained from the Oashore Station managers, as illustrated in Figure 3. A key criterion for the inclusion of these explanatory variables was the availability of spatial data with sufficient resolution to detect local variation across the site. For this reason, some potential explanatory variables such as soil properties, mean annual temperature, and precipitation were not considered. However, elevation was used as a proxy for both temperature and rainfall, with Banks Peninsula known to have a gradient of reducing temperature and increasing precipitation as elevation increases (Wilson 2003). The adequacy of these explanatory variables was confirmed by the absence of residual spatial autocorrelation, as discussed below. All explanatory variables were checked for collinearity to ensure they were not highly correlated, with all variables satisfying the collinearity threshold (variable inflation factor < 5) (Pituch & Stevens 2016).

Two separate analysis methods were used to evaluate the relationship between natural regeneration and these explanatory variables, being random forest and binary logistic regression. The reason for the use of dual analysis methods was to limit the potential shortcomings of each. For example, although random forest is able to cope with complex nonlinear relationships (Cutler et al. 2007; Moreno-Fernández et al. 2015), it is primarily focussed on prediction rather than explanation (Couronné et al. 2018) and may result in selection bias when using a combination of continuous and categorical predictors (Boulesteix et al. 2012). In contrast, binary logistic regression provides the ability to more directly assess the relationship between the explanatory variables and the dependent outcome, but is subject to several critical distributional assumptions that must be satisfied in order for the results to be accurate and reliable (Stoltzfus 2011). The use of these two methods in combination provides the opportunity for complementary and comparative results that provide a more robust understanding of natural regeneration patterns and processes.

The first analysis method was a random forest classification model, which is a form of machine learning using the random forest algorithm (Breiman 2001) and was carried out using the Forest-based Classification and Regression tool in ArcGIS Pro. The key inputs to the model were the sample points for the dependent variable, labeled as either regeneration or no regeneration. Explanatory variables were created as separate rasters, which were then extracted to the dependent variable point layer as additional attributes. Explanatory variables were selected for inclusion in the model following a backward selection approach. Interactions between explanatory variables were not explicitly modeled. The model incorporated 2000 decision trees, which was found to be the optimum tree size to improve model accuracy. Data-driven default settings were used to determine all other model hyperparameters, with an average tree depth of 22 and two variables used for each split. The model was trained using 80% of the data, with the remaining 20% of the data excluded for use in 50 separate validation runs. The variable importance measure (VIM) was calculated to assess the influence of each explanatory variable. Further information on the relationship between the explanatory variables and regeneration was obtained through the creation of partial dependence plots, which can reveal whether the relationships are linear or more

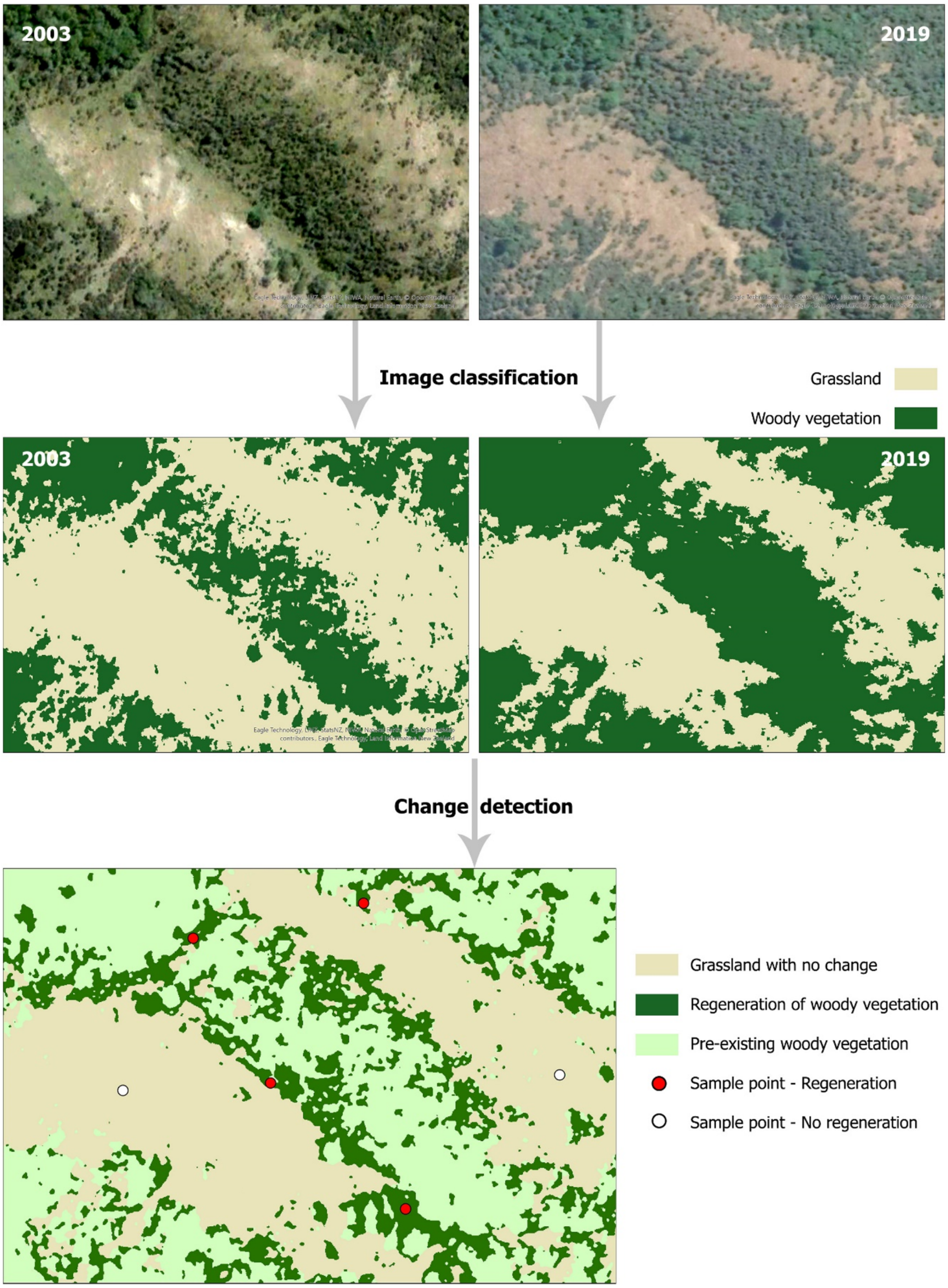

Figure 4. Extracts from application of method to Oashore Station, including: (top) base aerial images for 2003 and 2019; (middle) output of image classification converting each image into classified land cover maps of "grassland" and "woody vegetation"; and (bottom) change detection raster based on comparison of image classification outputs identifying areas of regeneration and no regeneration.

complex (Couronné et al. 2018). The accuracy and reliability of the model was tested using the mean squared error (MSE) and a confusion matrix.

The second analysis method was binary logistic regression, which was carried out in IBM SPSS Statistics software v28.0.0.0 (IBM Corp, Armonk, NY, U.S.A.) using the same sample points as the random forest analysis. All relevant assumptions for a binary logistic regression were tested to ensure that the model was appropriate, including the need for a binary dependent variable, observation independence, no multicollinearity among explanatory variables, no extreme outliers, and a sufficiently large sample size (Stoltzfus 2011). The assumption of a linear relationship between explanatory variables and the log odds of the dependent variable was checked using the Box-Tidwell test (Tabachnick & Fidell 2007). To ensure observation independence, the standardized model residuals were tested for spatial autocorrelation using the Global Moran's I test (Carl & Kühn 2007). The model was run using a backward stepwise selection approach, where all explanatory variables were added and sequentially removed based on their significance values. A significance value and odds ratio (Exp (*B*)) were calculated for each explanatory variable in the model to help understand the nature and strength of the relationship between explanatory variables and natural regeneration and to complement the insights gained from the random forest model.

Results

Model Variables, Assumptions, and Accuracy

For the random forest model, all explanatory variables were included in the model, which is generally the preferred approach when the primary objective is the identification of relevant factors (Degenhardt et al. 2019). The model produced an MSE of 20.48, indicating that 79.52% of predictions under the model were correct. This was similar to the overall accuracy of 80.40% calculated by the confusion matrix, which represents the frequency of correct classifications compared to the total number of confusions.

For the binary logistic regression, the "distance to woody vegetation" variable was log transformed to ensure a linear relationship with the log odds of the dependent variable. All other assumptions were satisfied. The Global Moran's I test on the model residuals produced a nonsignificant p value (0.918) and a Moran's I value of −0.007, which indicated there was no clearly identifiable spatial pattern of regeneration that was not explained by the explanatory variables. The combination of explanatory variables that resulted in the best overall accuracy was distance to woody vegetation, woody vegetation within 25 m, and years without cattle, with all other variables excluded. The model produced a chi-squared value of <0.01, indicating a significant improvement on the null model. The McFadden's pseudo r-squared value was 0.507, which means that the model's predictive performance improved by 50.7% by the addition of the explanatory variables and is a strong improvement in fit (Pituch & Stevens 2016).

What Was the Rate of Natural Regeneration of Woody Vegetation on Oashore Station?

Between 2003 and 2019, approximately 18 ha of Oashore Station experienced observable change from grassland to woody vegetation via natural regeneration. This represents approximately 3.8% of the total grassland area on the site at the start of the study period and equates to an annual rate of natural regeneration over 16 years of approximately 0.2% per year. Most of Oashore Station (453 ha or 96.2% of the grassland area) had no detected evidence of natural regeneration. The location and extent of natural regeneration on Oashore Station is identified in the change detection raster in Figure 5. Site visit observations indicated that restored shrubland was predominantly small-leaved indigenous shrub species that are less palatable to livestock (Wardle et al. 2001), including *Discaria toumatou* (matagouri), *Muehlenbeckia complexa* (scrub pōhuehue), *Carmichaelia australis* (New Zealand broom/tarangahape), and various *Coprosma* species.

Which Factors Influenced the Presence or Absence of Natural Regeneration?

The most important factor determining the occurrence of natural regeneration was the proximity to existing woody vegetation. The other explanatory variable that had a notable influence was the number of years that an area had been free from cattle grazing. These results were broadly consistent under both random forest and binary logistic regression and are presented in more detail below.

The study incorporated two uncorrelated variables representing the proximity to existing woody vegetation: distance to the nearest woody vegetation and the percentage of woody vegetation within a 25 m radius. These two variables had the highest VIMs in the random forest model 13.66% and 13.44%, respectively. Examining these relationships in more detail, Figure 6 illustrates a negative relationship between increasing distance to existing woody vegetation and the occurrence of natural regeneration. Locations that were immediately adjacent to existing woody vegetation (i.e., within 2 m) had the highest probability of experiencing natural regeneration. This relationship declined steadily out to approximately 20 m away from existing woody vegetation, beyond which the probability of regeneration started to level out and remained at a much lower value than closer areas. Figure 7 illustrates the inverse pattern for the percentage of existing woody vegetation within a 25 m radius, with the probability of natural regeneration increasing as the percentage of vegetation increased. If there was no existing woody vegetation within a 25 m radius, the probability of regeneration was very low. However, even a small amount of existing woody vegetation (e.g., 2% within 25 m) dramatically increased the probability of regeneration. There was a more gradual increase in probability from 5% up until approximately 50% existing vegetation cover, at which point there was little further change.

For the binary logistic regression, increasing distance to woody vegetation was found to have a statistically significant negative relationship with natural regeneration ($p < 0.01$; Exp (*B*) 0.346), which is consistent with the random forest model. In contrast, the amount of woody vegetation within 25 m was slightly above the significance threshold (p value 0.097, Exp (*B*) 1.021), indicating that it was the least influential of the two proximity variables. Nonetheless, this factor was retained in the binary logistic regression as removing it reduced the overall predictive accuracy of the model.

Other than existing woody vegetation, the next most important explanatory variable identified in the random forest model was the length of time that an area had been free from cattle grazing, with a VIM of 12.99%. The partial dependence plot demonstrated a consistent positive trend between natural regeneration and the number of years that cattle grazing had been excluded (Fig. 8), with the highest probability of regeneration in areas that had been free from cattle grazing for the longest time. Confirming the importance of this variable, the number

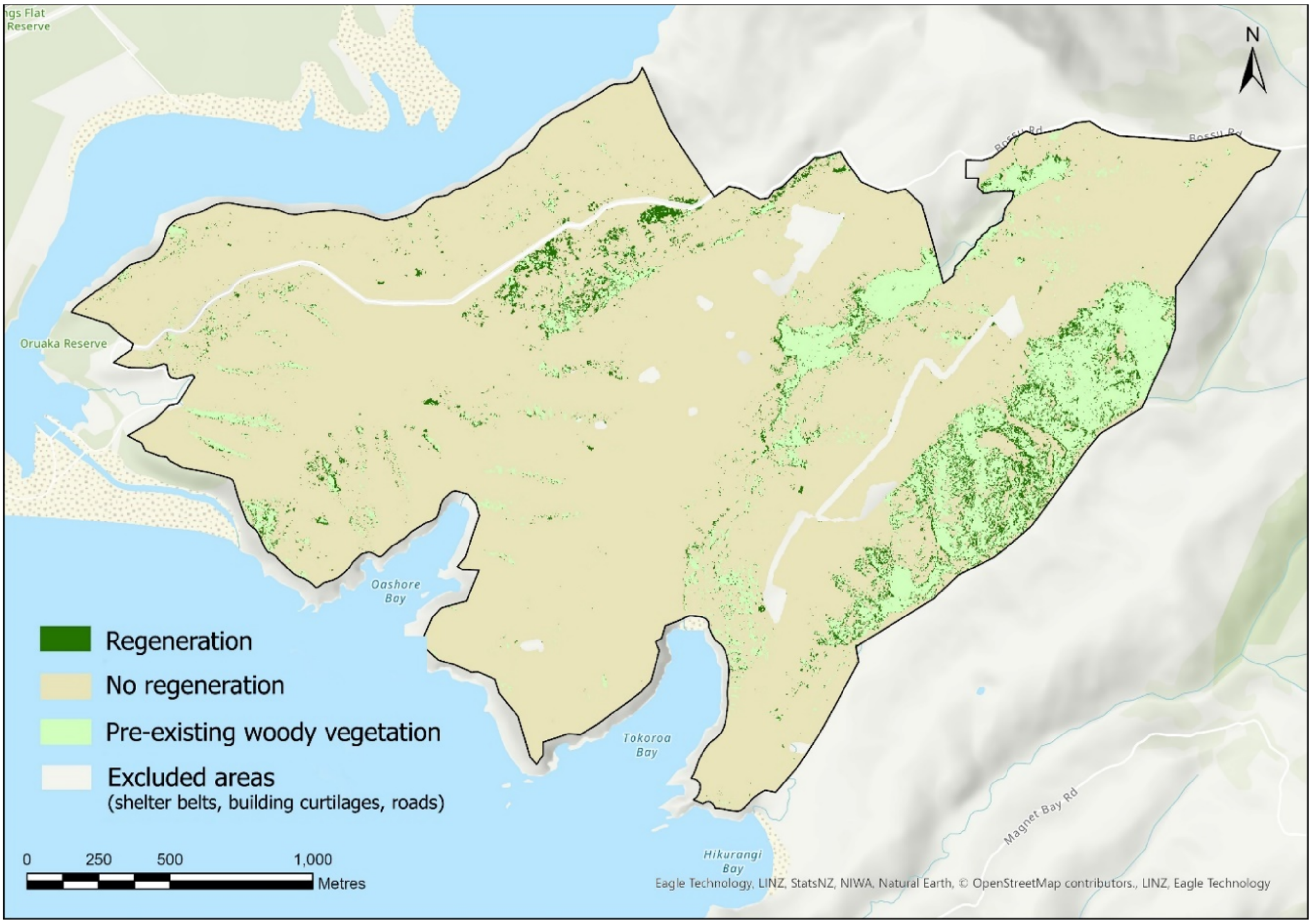

Figure 5. Areas on Oashore Station that regenerated from grassland into woody vegetation between 2003 and 2019 (3.3%) and grassland that remained unchanged (83.9%). Areas of pre-existing woody vegetation and excluded areas (shelter belts, building curtilages, roads) that were clipped from the classified images are also identified.

of years without cattle grazing was also identified as having a statistically significant positive relationship with natural regeneration under the binary logistic regression ($p < 0.01$; Exp(B) 1.230).

All other explanatory variables produced lower VIMs than the factors described above and were not statistically significant in the binary logistic regression. The results for all explanatory variables under both analysis methods are summarized in Table 1.

Discussion

Observed Rate of Natural Regeneration of Woody Vegetation

This study revealed a low rate of natural regeneration of woody vegetation from pasture on Oashore Station of approximately 0.2% per year. This quantifies the more general findings regarding slow colonization of grassland by forest plants in similar locations (Reay & Norton 1999) and provides an overall rate of regeneration across an entire site that is lacking in other studies in temperate regions utilizing representative field plots (Mason et al. 2013; Bergin & Kimberley 2014; Forbes et al. 2021). The rate of regeneration is broadly comparable to international studies using remote sensing methods, with tree cover in tropical regions of Brazil (which typically experience faster growth) found to increase by 0.3% per year (Crouzeilles et al. 2020; Borda-Niño et al. 2021) and 0.4% per year (de Rezende et al. 2015). The regeneration rate calculated in this study is an overall figure for the entire site, much of which was under continued grazing pressure for at least part of the study period, with unquantified impacts of feral browsers. Given the detrimental impact of mammalian browsing on natural regeneration (Wilson 1994; Smale et al. 2008) (discussed further below), rates of regeneration may differ in environments where all browsing is excluded.

An important practical implication of this slow rate of change is that it may limit the ability of a landowner to qualify for financial incentives (such as carbon credits), which can provide valuable income to support natural regeneration projects. This issue is of international relevance, as natural regeneration is often found to be incompatible with financial incentives schemes that are based on a more orderly and predictable trajectory of forest

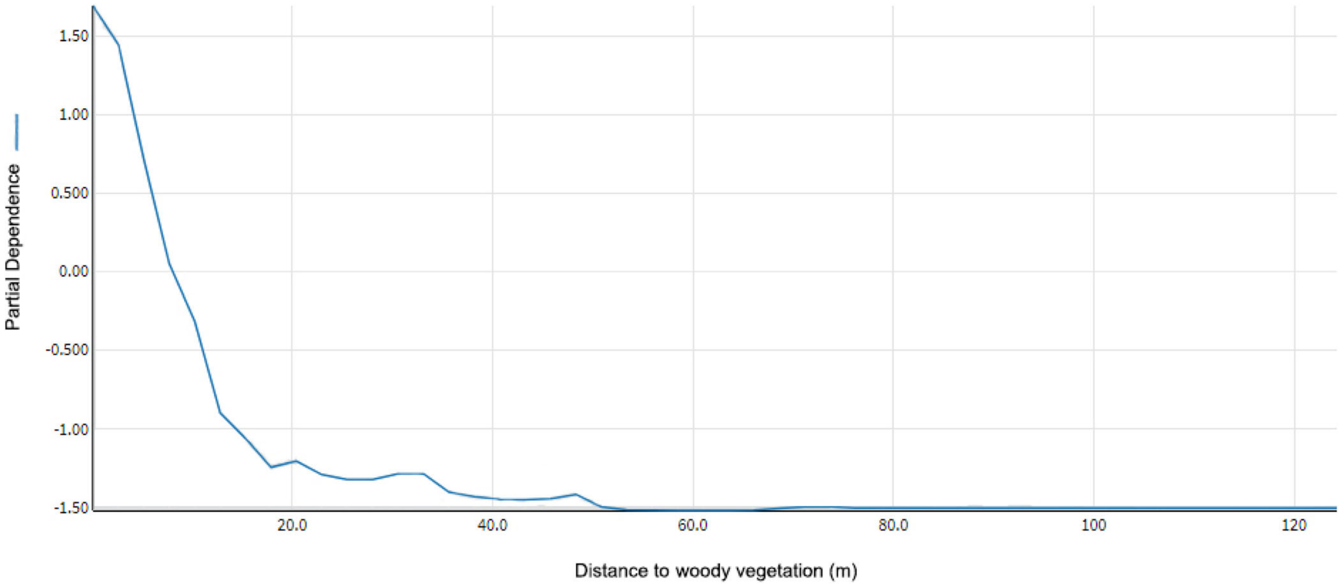

Figure 6. Partial dependence plot illustrating that sample points with a short distance to the nearest woody vegetation had the highest probability of natural regeneration.

restoration (Chazdon & Guariguata 2016). Although natural regeneration is cheaper than active restoration techniques, it still has direct financial costs for measures such as fencing and maintenance (Zahawi et al. 2014). These costs and the lack of immediate income from regenerating areas may deter many hill-country landowners from setting aside land for natural regeneration, despite its marginal value for continued farming activity. In the New Zealand context, landowners will generally not gain any income from carbon credits under the New Zealand Emissions Trading Scheme until the regeneration has progressed to a sufficient stage, including a minimum area of 1 ha with the presence of adequate forest species (Ministry for Primary Industries 2015). The slow rate of natural regeneration will result in landowners waiting a long time before receiving any income from carbon credits, which is likely to discourage them from restoring this land to forest. Further research is needed to develop more effective policies and programmes for encouraging forest restoration among hill country landowners that reflect the slow rate at which change is likely to occur.

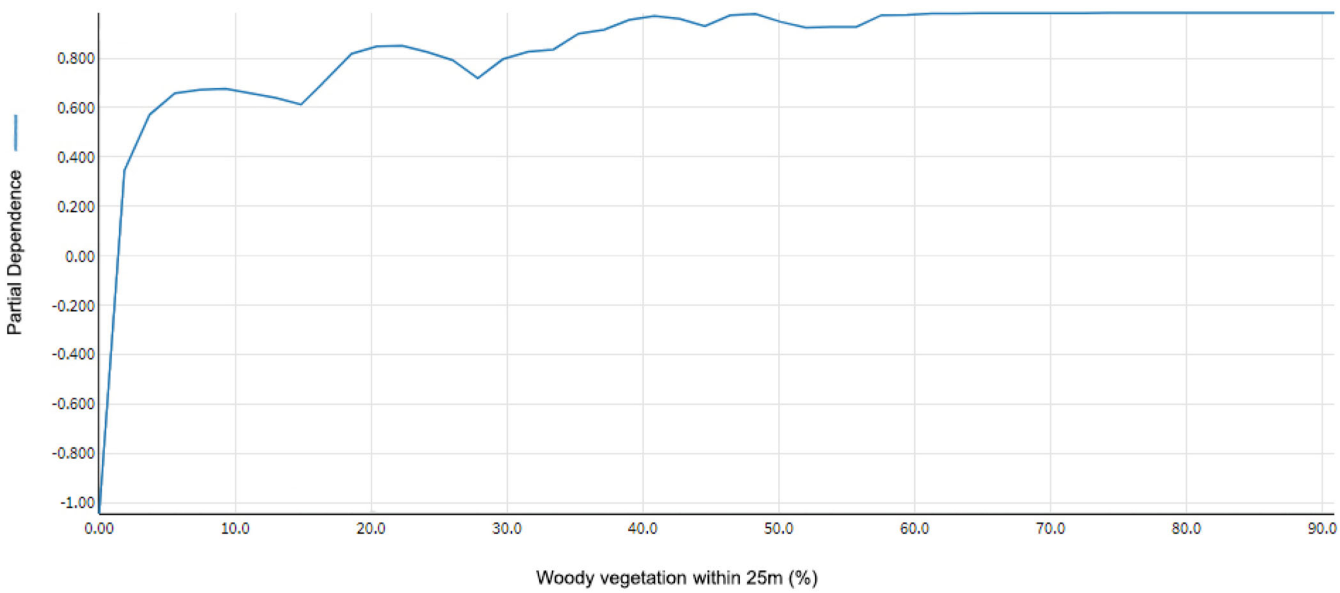

Figure 7. Partial dependence plot illustrating that sample points with a high proportion of woody vegetation within a 25 m radius had the highest probability of natural regeneration.

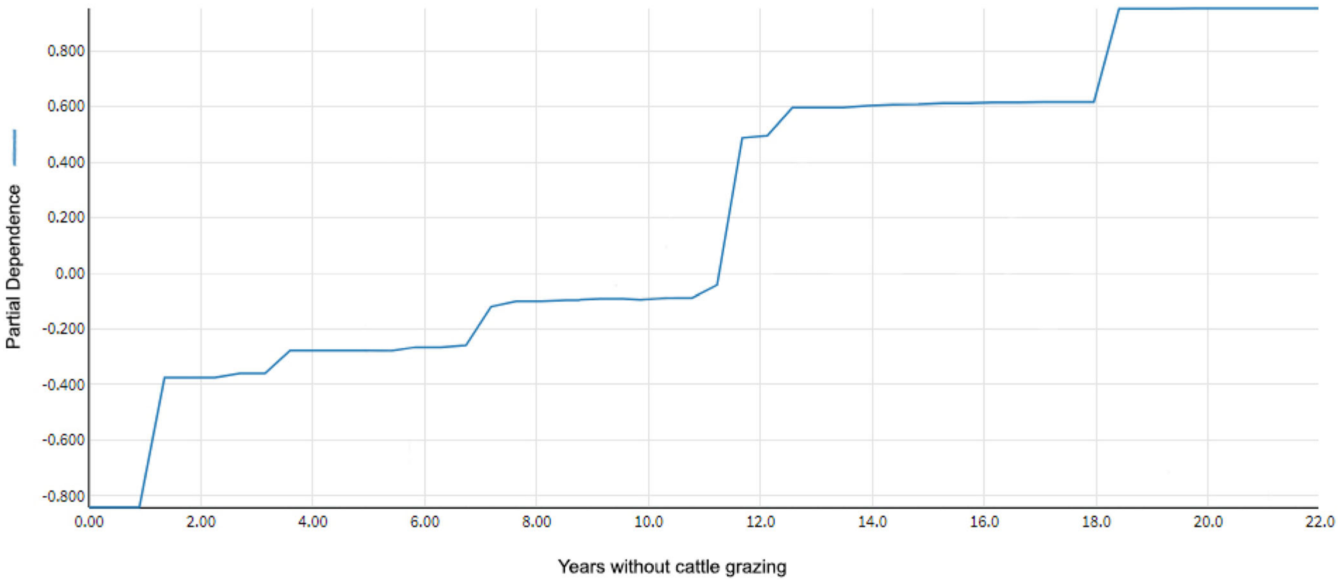

Figure 8. Partial dependence plot illustrating that the longer an area had been without cattle grazing, the higher the probability of regeneration.

Table 1. Variable importance measures (VIM), significance values, and odds ratios for explanatory variables in the random forest model and binary logistic regression model.

Explanatory variable	*Random forest VIM*	*Binary logistic regression*	
		Significance	*Exp*(B)
Distance to woody vegetation	13.66%	<0.01	0.346
Woody vegetation within 25 m	13.44%	0.097	1.021
Years without cattle	12.99%	<0.01	1.230
Topographic wetness	12.47%	N/A	N/A
Years without sheep	10.78%	N/A	N/A
Solar radiation	10.22%	N/A	N/A
Slope	10.15%	N/A	N/A
Elevation	10.02%	N/A	N/A
Aspect	6.31%	N/A	N/A

The slow rate of natural regeneration in marginal hill farmland creates significant challenges for achieving ambitious objectives for permanent indigenous forest, such as the New Zealand Climate Change Commission's goal of establishing 300,000 ha of new indigenous forest by 2035. Given the low amount and rate of change, significantly more than 300,000 ha would need to be set aside to achieve the Commission's goal if relying solely on natural regeneration and MIM. Furthermore, even if a sufficient area is dedicated to this purpose, all that may be achievable by 2035 is the initial transition from grassland to some form of woody vegetation, which is only the first successional stage in a long process toward the establishment of indigenous forest. If a faster rate of natural regeneration is desired, supplementary forest regeneration strategies and more active management may be necessary to alleviate the constraints on natural regeneration in temperate grassland.

Influence of Abiotic Environmental Factors on Natural Regeneration

Existing Woody Vegetation. The most important factor that influenced whether regeneration occurred was the presence of existing woody vegetation. Areas with more existing woody vegetation had a significantly higher prospect of experiencing natural regeneration, regardless of other factors. This finding is consistent with other studies, which have identified the presence of existing woody vegetation as an important factor for natural regeneration by providing essential seed sources (Molin et al. 2018; Crouzeilles et al. 2020; Grinand et al. 2020), limiting abiotic stress (Mason et al. 2013) and creating localized shade that reduces competition from light-demanding exotic species that pose a significant barrier to seedling establishment (Reay & Norton 1999; Miller & Wells 2003; Ledgard & Davis 2004). The role of existing woody vegetation is particularly important in the study context given the short-lived seed banks of New Zealand indigenous species (Rowarth et al. 2007).

The highest probability of regeneration was in areas immediately adjacent to the edge of existing woody vegetation. No other known studies quantify the extent of this influence for regeneration in temperate grassland. However, this pattern is consistent with the observations of Esler (1967) and Wilson (1994), which suggest that the shade provided by existing woody vegetation reduces grass growth on adjacent land and enables gradual encroachment from the vegetation boundary. This pattern may also be related to the dispersal limitations of regenerating species. The dominant regenerating species on the site possessed a variety of dispersal mechanisms, including dispersal by birds and lizards (*Muehlenbeckia* and *Coprosma* species), ballistic projection (*D. toumatou*), and dispersal of seed pods via gravity and wind (*C. australis*) (Thorsen et al. 2009). Although mechanisms such as avian dispersal and wind are capable of long-distance dispersion, other methods such as ballistic projection and dispersal by lizards have a more limited range (Thorsen et al. 2009; Wotton et al. 2016). Due to the limitations of remote sensing, it was not possible to detect whether different species of woody vegetation exhibited different regeneration patterns. Further research is required to determine whether dispersal mechanisms have a significant influence on the location of natural regeneration.

Based on the positive relationship between natural regeneration and existing woody vegetation, it is important that landowners have a clear understanding of the location of such vegetation to implement targeted and effective natural regeneration strategies. For example, farmers should focus on areas that have the highest proportion of existing woody vegetation and consider fencing such areas for grazing exclusion and pest management. Given the high cost of fencing in hill country landscapes, it is not always feasible to erect new fences around small patches of existing vegetation. A more practical strategy may be to use existing fences to exclude livestock from entire paddocks where woody vegetation is located. This would reduce fencing costs, promote the regeneration of the adjacent pastureland, and increase the potential for carbon credits as new areas of vegetation are established over time (Thompson 2019). Where woody vegetation is absent from paddocks, natural regeneration is substantially restricted due to insufficient availability of seed propagules, high competition from pasture, and increased abiotic stress that reduces seedling survival. If natural regeneration is to be pursued in such environments, more active and costly forest regeneration strategies will be required, such as the introduction of nurse species to facilitate tree seedling emergence (Padilla & Pugnaire 2006) and applied nucleation, where woodland islets of indigenous species are planted to enhance seed dispersal and seedling establishment (Benayas et al. 2008; García et al. 2020; Holl et al. 2020). Introduced woody vegetation patches could be designed to maximize the lengths of their edges given the beneficial edge effects of woody vegetation. Although natural regeneration exists on a spectrum of human intervention (Di Sacco et al. 2021), it is acknowledged that such approaches represent a shift toward assisted regeneration and away from lower cost strategies such as MIM.

Other Abiotic Environmental Factors. Other than existing woody vegetation, there were no clear or significant relationships between any other abiotic environmental variables and natural regeneration. This differs from some studies that have found other factors to have a significant impact on natural regeneration, which may be due to environmental variation on different sites. For example, Mason et al. (2013) found that mean annual temperature was a significant factor, but only where it dropped below 9°C. Given that the mean annual temperature across Oashore Station exceeds 9°C (Land Environments New Zealand spatial data), temperature (measured using elevation as a proxy) was not a significant variable. Similarly, Forbes et al. (2021) found that elevation was a significant factor influencing natural regeneration on a site with elevation ranging between 320 and 658 m. In contrast, most of Oashore Station is well below 320 m, which may explain why elevation was not a significant explanatory variable in this study.

In addition to environmental variation, the species of regenerating vegetation can affect which factors influence natural regeneration. For example, Príncipe et al. (2014) found that solar radiation was a significant factor for the regeneration of Holm Oak seedlings in a semiarid region of Portugal, which has a similar climate to Oashore Station and comparable values for estimated solar radiation. However, the survival rates of Holm Oak seedlings are known to be positively influenced by the availability of moisture and shade (Benayas et al. 2008). This can be contrasted with the dominant regenerating shrub species on Oashore Station (such as *D. toumatou* and *M. complexa*), which are well adapted to survive in dry conditions (Williams 2005). These comparisons demonstrate that the characteristics of a site and the regenerating species are likely to influence where, when and what natural regeneration occurs, so caution is needed when applying the results of this study to other areas of marginal hill farmland (Pawley & McArdle 2018). Further research is needed to determine to what extent the findings of this study are generalizable to other hill country settings with different biophysical characteristics and vegetation communities.

Influence of Cattle and Sheep Grazing on Natural Regeneration

A key finding of this study was that the presence of cattle grazing had a significant negative impact on natural regeneration. This relationship can be contrasted with two other New Zealand studies, where the presence of cattle was found to positively influence natural regeneration of totara (*Podocarpus totara*) (Miller & Wells 2003; Bergin & Kimberley 2014). This may be due to differences in the species of regenerating woody vegetation, with totara known to be relatively unpalatable to cattle (Bergin & Kimberley 2014). The impacts of cattle are also likely to be influenced by the intensity of grazing (Levy 1970), which varied over time and space on the site and was not assessed in this study due to a lack of historical data. Although the impact of cattle grazing on temperate forest vegetation can be context and species dependent (Augustine & McNaughton 1998; Öllerer et al. 2019), for sites with a similar vegetation composition to Oashore Station, it is suggested that cattle grazing should be reduced or removed to maximize the regeneration of woody vegetation in open pasture. This strategy could be targeted to areas near existing woody vegetation where natural regeneration has the highest prospect of success.

In relation to sheep grazing, it is not possible to draw any definitive conclusions due to the absence of a statistically significant relationship (positive or negative) between sheep grazing and natural regeneration. However, it is interesting to contrast these findings with those in relation to cattle, where a significant negative impact was observed. It is well recognized that different livestock species can have differing impacts on woody vegetation (Adams 1975). In a global review of the impacts of livestock grazing on temperature forest vegetation, Öllerer et al. (2019) noted that sheep mainly cause damage by browsing, whereas cattle can also cause damage by trampling and rubbing.

Cattle are also more likely to prevent woody scrub development by direct consumption and opening previously closed scrub (Öllerer et al. 2019). This is consistent with the findings of this study, which highlights that cattle have more significant negative impacts on regeneration compared to sheep.

Regeneration of woody vegetation did occur in some parts of the site where sheep grazing was present, which was primarily smaller leaved shrub species that are known to be less palatable to sheep (Wardle et al. 2001). Although this study relied on remote sensing and did not involve a systematic field survey of species, site visit observations indicated that where sheep grazing was present, there was a general absence of broadleaf palatable seedlings, which are essential for the long-term succession to biodiverse indigenous forest (Wilson 1994; Forbes et al. 2021). This is consistent with Smale et al. (2008), which found that the understory of grazed forest fragments contained almost no seedlings of existing canopy species and that the long-term maintenance of forest fragments was not viable without the complete exclusion of livestock. Further research is needed to better evaluate the potential costs and benefits of sheep grazing on different stages of the natural regeneration process and the effect of selective grazing on the species composition of indigenous temperate forest.

The exclusion of stock from certain areas of the site was achieved using post and wire fencing, which may not have effectively prevented stock access at all times. In addition, despite pest control efforts, the site was subject to unquantified browsing from feral mammals (including goats, possums, hares, rabbits, and deer), which can significantly reduce palatable broadleaf species in New Zealand forests (Wardle et al. 2001; Wright et al. 2012). These uncontrolled factors could not be considered due to a lack of accurate spatial data on stray and feral browsers. However, this is a typical scenario for hill farmland, where complete exclusion of stock through deer fencing and eradication of mammalian pests is prohibitively expensive and impracticable for landowners. The findings of this research are therefore representative of a low-cost MIM strategy to support natural regeneration that reflects the challenges and constraints faced by many hill country landowners. In this context, although slow rates of regeneration should be expected, the initial transition from grassland to woody vegetation can be enhanced through strategic prioritization of areas with the highest coverage of existing woody vegetation and the exclusion of cattle grazing. With appropriate financial and practical support, active and supplementary management approaches may be utilized to hasten the achievement of national and global forest restoration objectives.

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