Patterns of past and recent conversion of indigenous grasslands in the South Island, New Zealand

Emily S. Weeks[1*], Susan Walker[2], John R. Dymond[1], James D. Shepherd[1] and Bruce D. Clarkson[3]

[1]Landcare Research, Private Bag 11052, Palmerston North 4442, New Zealand
[2]Landcare Research, Private Bag 1930, Dunedin 9054, New Zealand
[3]The University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
*Author for correspondence (Email weekse@landcareresearch.co.nz)

Published online: 31 October 2012

Abstract: We used recent satellite imagery to quantify the extent, type, and rate of conversion of remaining indigenous grasslands in the inland eastern South Island of New Zealand in recent years. We describe the pattern of conversion in relation to national classifications of land use capability and land environments, and ecological and administrative districts and regions. We show that although large areas of indigenous grasslands remain, grassland loss has been ongoing. Indigenous grassland was reduced in the study area by 3% (70 200 ha) between 1990 and 2008. Almost two-thirds of post-1990 conversion occurred in threatened environments with less than 30% of indigenous cover remaining, primarily in the Waitaki, Mackenzie and Central Otago administrative districts. This conversion occurred primarily on non-arable land. In the Mackenzie and Waitaki districts the rate of conversion in 2001–2008 was approximately twice that in 1990–2001. Opportunities to protect more of the full range of indigenous grasslands lie with the continuing tenure review process in these districts.

Keywords: land tenure; loss of indigenous habitat; rate of habitat loss; remote sensing

Introduction

Most of the world's indigenous grasslands have been converted for agricultural activities (Groombridge 1992). Areas with better soils and more frequent rainfall have been mostly cleared for crops, while poorer quality grasslands have been left for rearing stock (Suttie et al. 2005). Globally there is limited information on the rate, type, and amount of change that is occurring in grassland ecosystems (Pearson & Ison 1997; White et al. 2000) and New Zealand is no exception. Without fundamental information on trends occurring in grasslands, researchers are unable to assess potential effects of land conversion on habitat and their associated biodiversity and ecosystem services, and policymakers lack the evidence needed to inform sound policy formation (Gluckman 2011).

With European settlement since the early 19th century, more than 60% of all New Zealand's indigenous habitats have been converted for agriculture and forestry (McGlone 2001). In the past the most threatened ecosystems have been considered to be lowland forests, coastal dunes and wetlands (Stevens et al. 1988; Ogden et al. 1998; Leathwick 2001; McGlone 2001), but remaining indigenous grasslands are also under threat from expansion of intensive agricultural land uses (Ewers et al. 2006; Walker et al. 2006).

Over 95% of New Zealand's remaining indigenous grasslands are located in the South Island. These indigenous tussock grasslands have a partially human induced origin and provide a range of important ecosystem services, i.e. water regulation and soil formation, including significant cultural value, to New Zealanders (McAlpine & Wotton 2009). Most of the lowland and montane regions of tussock grassland were created by burning and clearing of forest and shrubland by Māori c. 700–800 years BP, for hunting moa and encouraging the growth of bracken fern (*Pteridium esculentum*) (Stevens et al. 1988; Ewers et al. 2006; McWethy et al. 2010). Initially the short-tussock grasses (*Festuca* and *Poa* species) dominated, but within about 200 years were replaced by taller large *Chionochloa* species (McGlone 2001).

Mark and McLennan (2005) assessed the loss of New Zealand's indigenous grasslands since European settlement, comparing the pre-European extent of five major tussock grassland types against their current extent, using New Zealand Land Cover Database 1 (LCDB1; Thompson et al. 2003). They estimated that in 1840 (the beginning of formal European settlement) 31% of New Zealand was covered by indigenous grasslands dominated by endemic tussock-grass species, but that just 44% of this area remained in 2002, mainly in the interior areas of the South Island. Of this remaining area, approximately 28% had statutory protection with a bias towards the high-alpine areas. Mark and McLennan (2005) noted that remaining subalpine grassland communities still persisted but were severely degraded or modified, and very poorly protected.

With the release of New Zealand Land Cover Database 1 (1996/97) and 2 (2001/02) (LCDB1 & LCDB2; Thompson et al. 2003) New Zealand's more recent land cover change could be detected. However, though the automatic detection technology used to produce LCDB2 provided reliable estimates of change in woody vegetation, it was not informative for non-woody vegetation change. Identifying change in herbaceous vegetation is difficult because of temporal variability in soil moisture that has a greater effect than on woody vegetation (Dymond et al. 2006). Consequently, estimates of areas and rates of change in grasslands derived from comparisons of LCDB1 and LCDB2 are conservative and misleading (Walker et al. 2006).

Informal observations and limited quantitative data suggest that the conversion (land-use change) of New Zealand's indigenous grasslands in the South Island is proceeding rapidly. In addition, a process of reform of leasehold government land (colloquially called tenure review) has led to the division of substantial areas of former government-owned land into separate private ownership (Brower 2008; Walker et al. 2008; Mark et al. 2009). On land transferred to private ownership, reduced legislative constraints on vegetation clearance and reduced property size (Brower 2008) may be accelerating habitat loss for indigenous grassland species.

Aerial photography and satellite imagery provide appropriate data for monitoring conversion of land cover at regional or national scales. In recent years, substantial improvements in standardisation, illumination, and viewing geometry processing (Dymond & Shepherd 2004) – and in the spatial resolution of remote images – have significantly improved the ability to detect changes in grassland cover. Furthermore, in New Zealand, SPOT-5 imagery taken during the summer of 2007/08 provides a basis for updating land cover estimates based on Landsat images taken in the summers of 1989/90 and 2000/01. Here, we use these data to quantify the extent of conversion of indigenous grassland habitat between 1990 and 2008, and estimate the current (2008) extent of remaining indigenous grassland cover, and compare the rate of past (1840–1990) and recent (1990–2008) conversion in inland eastern South Island. We also describe the types and patterns of conversion that have resulted in loss of habitat for indigenous species in relation to land-use capability, administrative and ecological districts, and past loss and current protection for indigenous habitats in land environments.

Methods

Study area

To delineate objectively a study area that covers most of the indigenous grasslands in the South Island, we created a median reflectance image using SPOT-4 VEGETATION sensor satellite imagery, which provided daily coverage of the study area at 1-km resolution between 1990 and 2003. Spectral reflectance at each pixel was ranked from highest to lowest and the median-value pixel extracted. Median reflectance was preferred to mean to eliminate the effects of cloud coverage, which skews the average reflectance. Using ERDAS Imagine 9.1 (Leica Geosystems Geospatial Imaging 2003) the study area was then specified by selecting a GPS point of indigenous grassland from ground truth (field) data collected during the summer of 2007/08. From this point, all pixels with a median spectral Euclidean distance within 0.7 (7% spectral variation), and that were considered contiguous, were accepted. The 4.3-million-hectare study area encompasses the largest continuous extent of indigenous grasslands remaining in the South Island (Fig. 1).

Data pre-processing for detection of conversion

We used three sets of satellite images: Landsat images taken in the summers of 1989/90 (TM), and 2000/01 (ETM+), and

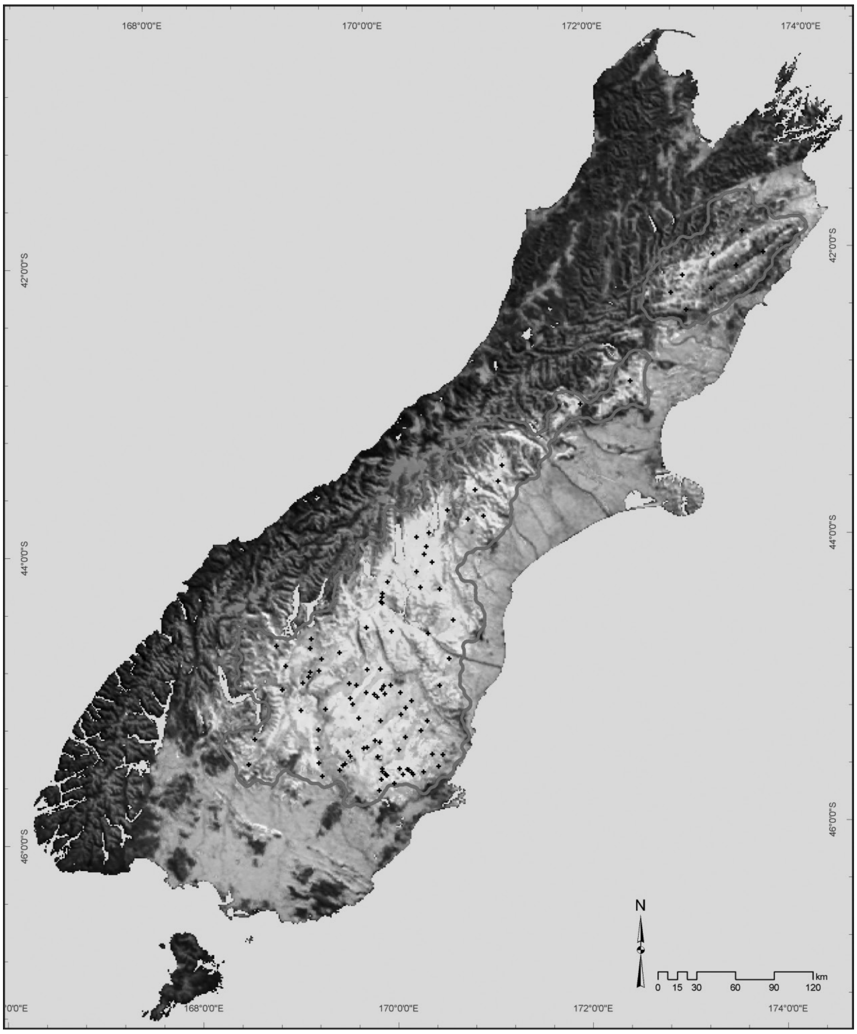


Figure 1. Study area (within red border) and distribution of ground field checks (250 location-specific photographs, +) made during the summer of 2009 (overlaid onto the median reflectance image created using VEGETATION sensor imagery (1990–2003) from SPOT-4 (bands 3, 4 and 2 mapped to red, green, and blue).

SPOT-5 imagery taken during the summer of 2007/08. The Landsat imagery was orthorectified and standardised for reflectance using methods described by Shepherd and Dymond (2003). ERDAS Imagine 9.1 was used to geometrically correct the raw SPOT-5 digital imagery. All three images were orthorectified to the New Zealand Map Grid using the SPOT-5 orbital pushbroom model and 15-m digital elevation model (DEM; Barringer et al. 2002, Shepherd & Dymond 2003). The standardised spectral reflectance was calculated assuming a nadir-viewing satellite sensor, and a 50-degree sun elevation. The 6S code was used to model irradiance and transmission of light through the atmosphere, and the WAKII model (Dymond et al. 2001) was used to describe and standardise the directional reflectance properties of the land cover and terrain. The standardised reflectance of the SPOT-5 imagery (bands 1, 2, 3, and 4) of invariant targets after application of cross-sensor response function calibration agreed with the standardised reflectance from 2001 ETM+ imagery (bands 2, 3, 4 and 5) to within ±0.01 or within 6% of the reflectance for slope angles up to 45 degrees (excluding sun incidence angles less than 5 degrees).

Mapping of conversion

We mapped grassland conversion within our study area for three periods: 1840–1990, 1990–2001, and 2001–2008. To map conversion from 1840 to 1990 we used the Mark & McLennan (2005) estimate of the extent of indigenous grasslands in 1840, and compared it with the 1990 extent of remaining indigenous grasslands. The 1990 indigenous grassland extent layer was estimated by combining the polygons of grasslands from the New Zealand Land Resource Information (NZLRI; Newsome et al. 2000) vector layer and the woody vegetation from EcoSat 1990 vector layer (Dymond & Shepherd 2004), and checking each polygon against the existing 1990 satellite imagery. Once the basic land cover map was corrected for digitising errors it was aggregated into a land cover classification system described in Appendix 1.

Conversion from 1990 to 2001 and from 2001 to 2008 was mapped using the three sets of satellite images. All conversion from an indigenous grassland cover type (as defined by the 1990 land cover map) to a non-indigenous cover type was manually digitised at 10-m resolution using the following band combination: Landsat (band-4, band-5, band-3) and for SPOT-5 (XS3, SWIR, XS2), which provided for best distinction between indigenous grassland cover and non-indigenous cover. For the purpose of this study we considered ‘indigenous grasslands’ to comprise a wide variety of low-productivity tussock grasslands and seral shrublands, in various states of modification, that retained indigenous plant species. These vegetation types are extensively managed (mainly for pastoral grazing), are characteristically brown or grey-coloured, and in our selected band combination are visualised as pale green-blue, because of the high reflectance of the red and medium-infrared bands. We mapped the conversion from indigenous cover to six land-use classes: planted forest, invasive exotic (wilding) trees, exotic pasture, cropland, settlement, and open-pit mining (Appendix 2). High-productivity ‘exotic pasture’ is readily distinguished from lower-productivity ‘indigenous grassland’ based on its orange-red colour (due to the high reflectance of bright green exotic grass and clover species, such as rye grass, white clover and red clover in the near-infrared band).

To map conversion (changes in land use) we used multiple sources of evidence, including information from satellite images, photographs, land-use databases, local knowledge, and field inspection. Satellite imagery was the primary source used for interpretation but was supplemented with existing land cover information, including aerial photography supplied by Terralink International (Wellington, New Zealand). The process used multiple (up to 6) ERDAS Imagine viewers, each containing one of the three dates of satellite imagery, the 1990 indigenous grassland cover map, and aerial photographs. Each polygon of change was digitised on top of the satellite imagery, using the area of interest (aoi) tool in ERDAS Imagine, and all polygons were converted to a single vector layer. The area of conversion during each period for each conversion type was then calculated.

Ground truthing (i.e. visual field inspection) was used both to train an operator before the mapping process and then to confirm conversion between 1990 and 2008. For training, an operator recorded 250 different GPS points of land-use/cover in the field. At each GPS point photographs were taken, the land-cover/use was recorded, and the corresponding visualised spectral signature was identified in the satellite imagery. A laptop computer was connected to a GPS unit allowing for continuous tracking of the current position against the background of the satellite image. This was achieved using ArcView software, the Digital Topographic Database (Land Information New Zealand) and GPS Utility (GPS Utility, UK) software.

The process of confirming conversion involved (1) operator investigation of each of the 375 conversion polygons in the field and (2) systematically traversing approximately 10 000 km of no-conversion from the ground and in the air, throughout the study area (Fig. 1). During the ground-truthing process we identified both errors of commission (conversion identified in the satellite imagery not in fact present on the ground) and errors of omission (conversion observed on the ground not correctly captured from the satellite imagery). Panoramic photographs were taken from the ground and oblique or vertical photos from the air. The aerial photographs were taken at 2000 m above sea level. In total these amounted to c. 500 location-specific photographs of different examples of conversion (Appendix 3). All mapping errors were corrected on returning from the field confirmation exercise.

Accuracy assessment

Once the final map of conversion from 1990 to 2008 was completed, the mapping accuracy of an operator was assessed using a purpose-built software package designed to manage on-screen ERDAS Imagine viewer content and enable a rapid pixel-by-pixel assessment (J.D. Shepherd, unpublished software application). Five hundred points were randomly sampled in areas mapped as ‘conversion’ and 2000 points in areas mapped as ‘no-conversion’. A second operator assessed whether conversion was correctly or incorrectly identified in order to produce a confusion matrix (Congalton 1991). From the confusion matrix we estimated the mapping accuracy of ‘conversion’, ‘no-conversion’ and overall classification accuracy. From the confusion matrix we also estimated the uncertainty of the change area using the method described by Dymond et al. (2008), which considers the relative area of ‘change’ and ‘no change’.

Mapping accuracy and uncertainty were not statistically measured for the 1840–1990 map because this was a combination of previously created maps, i.e. the 1840 grassland estimate of Mark & McLennan (2005), the NZLRI (Newsome et al. 2000), and EcoSat 1990 (Dymond & Shepherd 2004).

Rates of conversion

For each time period we estimated an average rate of conversion (following Liu et al. 1993). The rate of conversion, or loss, per year (r) was calculated as an average conversion for each period, using the formula:

$$r = \frac{(A_0 - A_1)}{(t_0 - t_1)},$$

where A_0 = area at time t_0, and A_1 = area at time t_1. This measure makes no assumptions about a loss model.

Analysis of patterns of conversion

As the basis for describing patterns of grassland conversion, we used a combinatorial analysis of datasets, run in GIS using the ArcSampling program developed by Landcare Research. The digitised vector layer of conversion was converted to a 25-m raster layer and was combined with a Land Use Capability (LUC) layer from the New Zealand Land Resource Inventory (NZLRI; Newsome et al. 2000), and layers from Land Environments of New Zealand (LENZ; Leathwick et al. 2003), the Threatened Environment Classification of Walker et al. (2006; Appendix 4), Protected Areas of New Zealand (PANZ), Crown-owned leased land), administrative regions and districts, and ecological districts (McEwen 1987). The ArcSampling program created a raster layer of all unique combinations of input classes, and tabulated the area of each unique combination for import into Microsoft Access. Microsoft Access and Microsoft Excel (2007) were used for subsequent calculations and tabulations.

Results

Conversion between 1990 and 2008

Within the study area, 70 200 (±5000) ha of indigenous grasslands were converted between 1990 and 2008 (Table 1, Fig. 2). Of this, c. 50 500 ha (71%) were converted for agriculture: 47 600 ha for pasture and 2900 ha for cropland. The remaining area was converted for afforestation (17 650 ha), mining (1900 ha) and urban development (150 ha). Though most of the afforestation was from planted trees (15 900 ha), some resulted from the spreading of wilding exotic trees (1750 ha). We estimate that our operator mapping accuracy was 97.4% (487/500) for conversion and 99.8% (1997/2000) for no-conversion. The uncertainty of our change estimates are ±7.5%, determined using the method of Dymond et al. (2008). Given this level of uncertainty, we generally report conversion areas only to the nearest 100 ha, except for small areas and rates of conversion where the 7.5% uncertainty becomes absolutely small.

There were some differences between the types of changes during the two periods. In the 11 years from 1990 to 2001, agriculture (25 300 ha), followed by afforestation (11 050 ha), accounted for most of the 38 100 ha of indigenous grasslands converted to a non-indigenous cover type, and mining converted a further 1700 ha. Very little grassland conversion for urban development (50 ha) was detected.

There was less (32 100 ha) change in total in the shorter period (7 years) from 2001 to 2008. During this time, 25 200 ha of grassland were converted for agriculture, almost as much as in the preceding 11 years. More land was converted for urban development (100 ha), and less land to afforestation (6600 ha) and for mining (200 ha), than in the preceding period.

These results show a particularly marked (67%) increase in the average annual rate of conversion of indigenous grassland to exotic pasture, from 2100 ha year^{-1} between 1990 and 2001 (11 years), to 3500 ha year^{-1} in the period 2001–2008 (7 years). The rate of conversion for exotic plantation forestry (the second largest cause of grassland conversion) remained steady at around 880 ha year^{-1} over both periods, while average annual afforestation, cropland agricultural, and mining conversion rates decreased markedly in the second period.

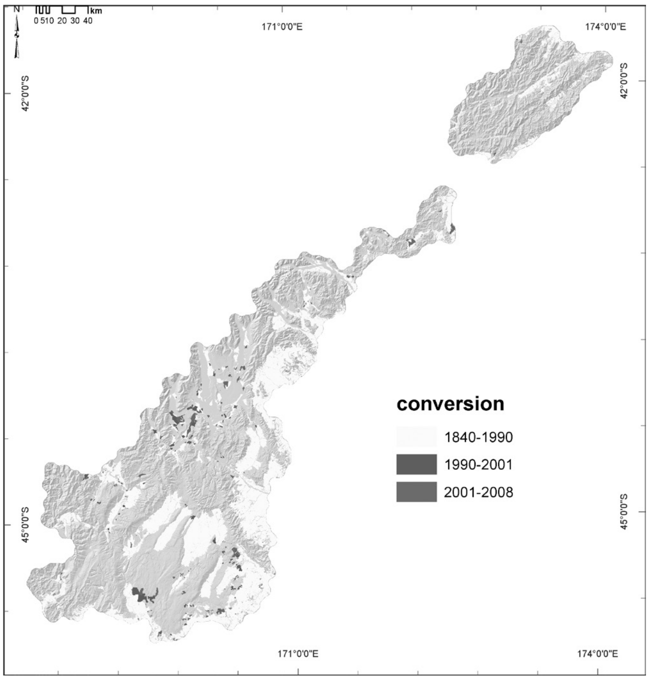


Figure 2. Grassland conversion recorded in three time periods. Light grey background represents areas not converted.

Table 1. Areas (ha) of indigenous grassland conversion by land-use type in two periods between 1990 and 2008 (see Appendix 1 for land cover associations for these cover types).

	Afforestation		Agriculture		Barren land		Total
	Planted	Wildling	Pasture	Cropland	Mining	Urban	
1990–2001	9700	1350	23 000	2300	1700	50	38 100
2001–2008	6200	400	24 600	600	200	100	32 100
Total	15 900	1750	47 600	2900	1900	150	70 200

Remaining indigenous grasslands

The dataset adapted from Mark & McLennan (2005) shows that in 1840 there were 3.31 million hectares of indigenous grasslands within our study area. We estimated that by 1990, 30.5% of these grasslands had been converted to a non-indigenous cover type (Table 2). The remaining 2.31 million hectares of indigenous grasslands provided a baseline for detecting grassland conversion between 1990 and 2008.

Indigenous grassland cover within the study area has continued to decline since 1990. Between 1990 and 2001, 38 100 ha of indigenous grassland were converted to a non-indigenous cover type. An additional 32 100 ha were converted between 2001 and 2008. By 2008, 3.2% (±0.2%) of the 1990 indigenous cover was converted, leaving 2.24 million ha of indigenous grasslands within the study area (Table 2, Fig. 3).

Rates of conversion

Between 1990 and 2001 the rate of grassland conversion was 3500 ha year^{-1} on average. This increased to 4600 ha year^{-1} between 2001 and 2008. This rate of conversion is lower than the 6700 ha year^{-1} on average between 1840 and 1990. In contrast, for the percentage loss of remaining grassland, the rate of conversion between 2001 and 2008 at 0.21% per year was larger than the 0.15% per year for 1990–2001 and the 0.20% for 1840–1990. However, there is considerable uncertainty associated with the 1840–1990 changes as the 1840 baseline is historical and must be uncertain, so there is probably no significant difference between the 1840–1990 and 2001–2008 estimates.

Administrative regions and districts

Most grassland conversion from 1990 to 2008 (65 590 ha) was concentrated in Canterbury and Otago administrative regions. Marlborough and Southland made up a small portion (<5%) of the study area, and less than 2% of grassland conversion was recorded in these regions.

Grassland conversion took place in 13 different districts (Table 3). Two-thirds of recorded conversion of indigenous

Table 2. Indigenous grasslands in 1840 (adapted from Mark & McLennan 2005) and extent remaining in 1990, 2001 and 2008, with total and percentage loss in the preceding time period. The total hectares and percentage loss since 1840 are shown in the last row. Estimate uncertainties were determined using the method of Dymond et al. (2008).

Year	Grasslands remaining (million hectares)	Loss in preceding time period (ha)	Percentage loss in preceding period
1840	3.31	-	-
1990	2.31	1 001 300	30.5
2001	2.27	38 100 (±3000)	1.7 (±0.12)
2008	2.24	32 100 (±2500)	1.5 (±0.11)
Total loss		1 082 500	33.6

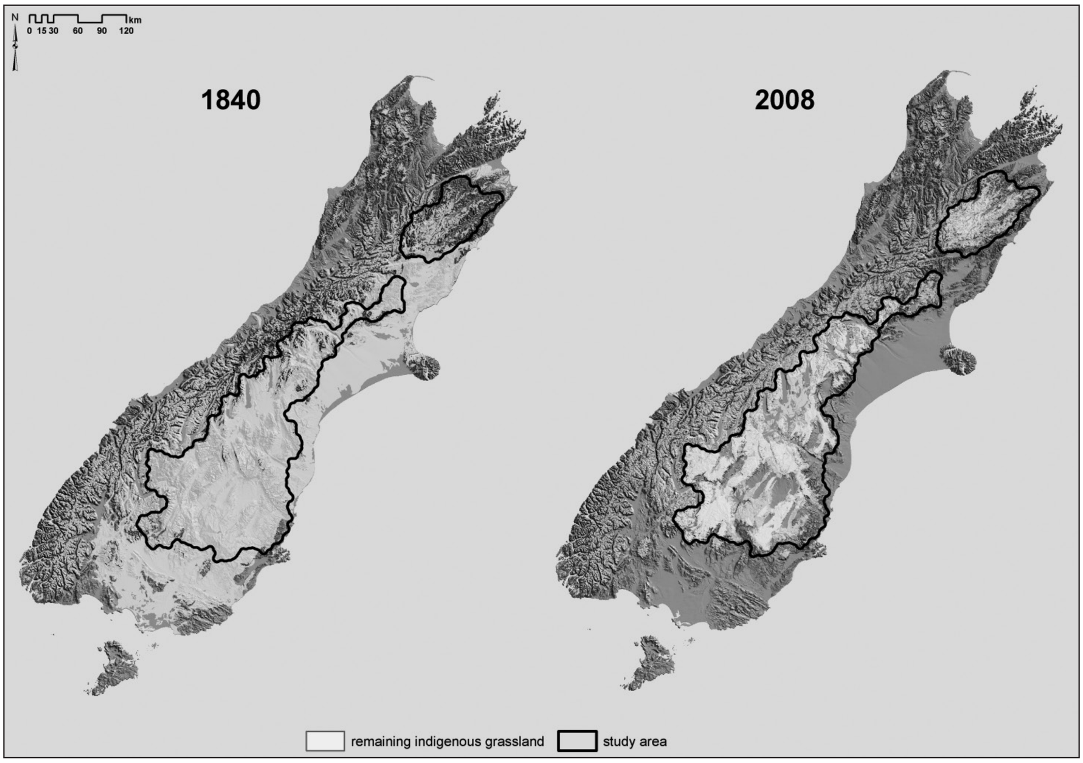


Figure 3. Original extent of indigenous grasslands in 1840 (adapted from Mark & McLennan 2005) and extent remaining in 2008. The black line indicates our study area.

Table 3. Area of remaining indigenous grasslands and recorded grassland conversions from 1990 to 2008 in the 13 administrative districts with land within our study area. For each district, the table shows total conversion (in all land use capability (LUC) classes) and in non-arable land only (LUC classes 6–8). The average rate (ha year^{-1}) of conversion in each district is shown for two periods (1990–2001 and 2001–2008). Grasslands remaining in 2008 are shown in total and in two tenure categories (protected private and crown land and crown pastoral lease), and the percentage of 1990 grassland area remaining in each category. Total area of conversion 1990–2008 estimate uncertainty is ±7.5%.

District	Total area remaining in indigenous grassland 1990 (ha)	Area of conversions (ha): Total		Area of conversions (ha): Non-arable land		Non-arable land as % of total conversions		Rate of conversion (ha year^{-1})		Area remaining in 2008 (ha)			Percentage of 1990 grassland area remaining in 2008	
		1840–1990	1990–2008	1840–1990	1990–2008	1840–1990	1990–2008	1990–2001	2001–2008	Protected	Crown leased	Total	Protected	Crown leased
Canterbury														
Mackenzie	311 200	127 700	11 400	71 400	7500	55.9	65.3	450	930	40 700	166 800	299 800	14	56
Waitaki	281 800	205 100	22 300	115 900	13 500	56.5	60.8	900	1700	43 100	107 800	259 500	17	42
Waimate	117 300	86 100	750	45 200	330	52.5	44.0	30	60	11 100	54 200	116 600	9	46
Ashburton	117 000	47 700	500	35 100	440	73.5	88.0	13	50	36 800	64 200	116 500	32	55
Selwyn	44 100	11 200	880	4500	480	40.0	54.1	2	90	5900	8700	43 200	14	20
Waimakariri	22 000	6200	2200	1800	14	28.3	0.6	140	160	2200	4600	19 800	11	23
Hurunui	103 000	42 400	2400	26 300	2100	62.0	87.3	140	210	6400	29 100	100 600	6	29
Otago														
Central Otago	651 000	230 800	15 800	57 500	12 000	24.9	75.7	990	700	55 400	265 200	635 200	9	42
Dunedin City	109 100	87 700	5800	48 000	2300	54.7	40.1	220	500	16 500	9200	103 300	16	9
Queenstown	190 900	33 500	2600	7500	400	22.5	15.5	200	60	27 000	10 500	188 300	14	6
Clutha	24 100	26 100	880	18 000	90	69.0	10.5	60	30	4500	8 300	23 200	19	36
Southland														
Southland	130 200	24 900	500	9200	100	36.8	19.2	12	50	18 400	97 700	129 700	14	75
Marlborough														
Marlborough	217 100	54 500	5300	53 000	300	97.2	6.0	360	190	32 600	115 100	211 800	15	54

grassland from 1990 to 2008 occurred in the Mackenzie (11 400 ha), Waitaki (22 300 ha), and Central Otago (15 800 ha) districts. More than half (56%) of recent conversion was on land classified as non-arable with moderate (LUC 6) to extreme limitations (LUC 8) to crop, pasture and forestry growth; we recorded 7500 ha, 13 500 ha, and 12 000 ha of non-arable land conversion in Mackenzie, Waitaki, and Central Otago districts respectively. These same districts showed marked increases in the percentage of total conversion on non-arable land between the pre- and post-1990 periods. Central Otago showed the greatest increase in percentage of total conversion of non-arable land from 1840 to 1990 compared to 1990–2008. Here there was a 50% increase in conversion of non-arable land from 1990 to 2008.

The Mackenzie and Waitaki districts (both within the Canterbury Region) also showed recent increases in the rate of conversion per year (Table 3), which approximately doubled during the second period (2001–2008). Although the rate of conversion per year increased in most districts in the second period (2001–2008), in Central Otago, Queenstown, Clutha and Marlborough districts there was a decrease.

The administrative districts with the largest extent of remaining grassland in 2008 were Mackenzie (299 800 ha), Waitaki (259 500 ha), and Central Otago (635 200 ha) (Table 3). These districts also had the most remaining grasslands under lease from the Crown in 2008 (166 800 ha in Mackenzie, 107 800 ha in Waitaki, and 265 200 in Central Otago), and the largest areas under protection (40 700 ha in Mackenzie, 43 100 ha in Waitaki, and 55 400 ha in Central Otago). Districts with the least remaining grasslands in 2008 were Selwyn (43 200 ha), Waimakariri (19 800 ha) and Clutha (23 200 ha), which also had <35% of their remaining grasslands protected.

Ecological districts

The study area includes parts of 11 ecological districts (ED; McEwen 1987) and all of the Mackenzie, Waitaki and Central Otago EDs (Table 4). All EDs showed a decrease in the remaining area of indigenous grasslands since 1840. Most EDs showed an increase in the rate of conversion from 2001 to 2008 compared with 1990–2001, but in Central Otago, but in Central Otago and the Lakes EDs the rate of conversion decreased (Table 4). Central Otago (363 900 ha), Pareora (214 000 ha), Lammerlaw (137 600 ha) and Mackenzie (125 400 ha) EDs had the greatest total area converted since 1840. The greatest recent increase in loss of remaining indigenous grasslands was in Mackenzie ED, where 11 900 ha were converted from 1990 to 2001, and 15 200 ha from 2001 to 2008. Large increases in areas converted were also seen in the Lowry, Puketeraki and Canterbury Foothills EDs, where the area of conversion more than doubled.

Threatened Environments and protection status

Three-quarters of total indigenous grassland conversion from 1840 to 2008 has occurred in environments that are mapped in the threatened environment classification (Walker et al. 2006) as having less than 30% of indigenous cover remaining (Fig. 4). The largest total area of historical grassland conversion (409 100 ha) was in 'Acutely Threatened' environments (those with <10% indigenous cover left; Walker et al. 2006). The second largest area (238 300 ha) was in 'Chronically Threatened' (10–20% of indigenous cover remaining), followed by 'At Risk' environments (those with 20–30% indigenous cover remaining). About 10% of grasslands found in 'Acutely Threatened' environments in 1840 remained in 2008 and 38% of those formerly present in 'Chronically Threatened' environments remained.

Environments with the smallest proportions of indigenous grasslands remaining were also those most prone to conversion in the last two decades (Fig. 4). In 'Acutely Threatened' environments, 20 700 ha of grasslands were converted between 1990 and 2008; 22 200 ha were converted in 'Chronically Threatened' environments, and 16 400 ha of 'At Risk' environments in this period. Rates of grassland loss (from 1990 to 2008, expressed as a proportion of grasslands

Table 4. Remaining area (ha), rate of conversion (ha year^{-1}) and area of conversion (ha) of indigenous grassland in each ecological district (McEwen 1987) within the study area.

	Remaining area (ha)				Rate of conversion (ha year^{-1})			Area of conversion (ha)			
Ecological District	1840	1990	2001	2008	1990–2001	2001–2008	1990–2008	1840-1990	1990–2001	2001–2008	Total
Clarence	76 900	44 900	44 900	44 600	0.5	39	16	30 000	5	270	31 300
Lowry	7000	1450	1450	410	1	140	60	5600	10	1000	6600
Puketeraki	109 000	60 600	60 300	59 100	26	185	90	50 400	290	1300	50 000
Canterbury Foothills	74 500	34 400	34 300	31 000	8	470	190	40 200	90	3300	43 500
Heron	221 400	133 800	133 700	133 100	14	79	40	87 600	150	550	88 300
Tasman	39 900	28 500	28 500	28 500	0.5	2	1	11 400	3	15	11 400
Pareora	324 300	110 700	110 500	110 300	16	30	20	213 600	180	220	214 000
Mackenzie	429 000	330 700	318 800	303 700	1080	2200	1500	98 300	11 900	15 200	125 400
Waitaki	234 900	178 100	177 900	177 000	20	130	60	56 800	220	900	57 900
Lakes	225 200	176 600	175 400	175 300	140	13	70	48 600	1550	90	50 300
Central Otago	959 200	611 600	602 000	595 300	960	800	900	347 600	10 600	5700	363 900
Lammerlaw	271 200	147 500	140 000	133 600	690	900	770	123 700	7600	6300	137 600
Mavora	32 200	26 200	26 200	26 100	0.5	7	3	6000	5	50	6100
Waikaia	117 700	82 600	82 600	82 600	0.5	6	3	35 000	5	40	35 100

Figure 4. Grassland conversion and remaining indigenous grasslands within the 'Threatened Environment Classification' categories of Walker et al. (2006). (a) percentage 1840 grasslands remaining and converted to date; (b) area of grasslands in 1840, remaining in 2008, and converted to date; (c) area converted from 1990 to 2008.

remaining in 1990) decreased markedly from the most to the least threatened environment classes. Only a very small proportion (1.4%) of the grassland conversion was within land environments with >30% indigenous cover remaining and more than 10% of their land area formerly protected for conservation (the Underprotected and Less Reduced and Better Protected categories of Walker et al. (2006)).

Discussion

Quantifying grassland conversion

A critical step in managing ecosystems is to take stock of their extent, condition, and capacity to continue to provide natural services. Our analysis quantifies the extent to which recent changes in land-use activities have further reduced and fragmented indigenous grasslands within inland eastern South Island, and how the pattern of land conversion has changed.

Grasslands in lowland environments that were most suitable for production were the first to be converted by European settlers: by 1990, non-indigenous vegetation had replaced most of the 1840 'baseline' indigenous grasslands mapped by Mark and McLennan (2005) on the Southland, Canterbury and coastal Marlborough plains, and in inland North Canterbury (Fig. 3). In 1990 the largest continuous extent of indigenous grasslands in 1990 remained within a 4.3-million-hectare area of inland South Island, which we used as our study area to assess recent change.

We show that although large areas of indigenous grasslands remain within this study area, grassland loss has been ongoing. About one-third (34%) of the original 3.3 million hectares of indigenous grasslands have been converted to non-indigenous land cover type in the last 168 years. More subtle forms of degradation of indigenous species habitat, which we did not measure here, are also likely to be ongoing as well as more widespread.

Within our study area, more non-arable land (as defined by Land Use Capability in the New Zealand Land Resource Inventory; Newsome et al. 2000) has been converted in the last two decades than in the period before 1990. This land is generally at mid- to low-elevation, and is characterised by gentle to moderate slopes, summer droughts, extreme winter and summer temperatures, high winds, and limited annual rainfall. Many of the soils that support these grasslands are relatively infertile or porous and erosion-prone, with degraded vegetation cover (due to overgrazing by rabbits and livestock) (Hewitt 1998). The pattern suggests a trend in grassland conversion from more productive to more marginal land over time.

Although several national inventories of remaining indigenous grasslands have been completed in recent years, these have relied on national land cover databases (LCDB). Specifically, use of LCDB1 (Mark & McLennan 2005), or comparisons of LCDB1 and LCDB2 (Walker et al. 2006), have led to underestimates of grassland conversion. For example, comparisons of LCDB1 and LCDB2 suggest that between 1996 and 2001 there were 2486 ha of change from tall-tussock grasslands to a non-indigenous cover class, for the entire country (Walker et al. 2006). We found there to be twice as much as this, within our study area alone, by 2001. Furthermore, Mark and McLennan (2005) estimated, based on LCDB2, that 77% and 82% of tussock grasslands remained in the Mackenzie and Waitaki EDs, respectively, in 2002, but our data suggest these were overestimates and that about 7% more conversion had actually taken place in each of these districts by 2002.

Although our findings confirm the limitations in the LCDB for detecting changes in grasslands noted by Walker et al. (2006), they suggest the LCDB2-based threatened environment classification is nevertheless a reasonably robust predictor of both past loss and recent conversion of South Island indigenous grasslands. Both past and recent conversion rates decrease across the six categories of 'threatened environment', with grassland conversion in the first three categories accounting for a high percentage (74%) of all grassland conversion in our study area between 1990 and 2008. As rates of grassland conversion on non-arable land increase, the remaining indigenous grasslands in intermediate 'threatened environment' categories (e.g. 3. At Risk and 4. Critically Underprotected environments) are likely to become increasingly vulnerable to conversion.

Limitations in the LCDB grassland classes are explained by technical difficulties associated with automatic detection of change in non-woody vegetation (Dymond et al. 2006).

Although higher resolution satellite data are now available and permit more accurate interpretations of land cover, measurements of grassland conversion will likely remain variable unless: (1) a more universally accepted set of definitions of grasslands is established, and (2) there is greater consistency in methods used to determine boundaries between forests and grasslands, and agricultural land/permanent pasture and grasslands. We suggest improvements in estimates of grassland land cover and conversion, and better representation of the heterogeneity of grasslands types, could be made by defining classes based on the structure and floristic composition of the vegetation rather than land uses (i.e. low-producing grasslands). Grassland classes should be defined using robust field sampling to establish the biotic component of the class (Newsome 1987), and be complemented by remote sensing technology that matches spectral signatures with each grassland class (Ferreira et al. 2003).

Types and rates of conversion

Our results suggest a trend towards intensification per hectare of land, within the South Island indigenous grasslands, and particularly towards more productive pasture. Two-thirds of the conversion we recorded between 1990 and 2008 was to exotic pasture. Methods of conversion usually involve oversowing with legume species (mostly white clover *Trifolium repens*) and exotic grass forage species, often accompanied by installation of irrigation infrastructure and increased application of fertilisers to attain desired productivity levels. The rate of this type of conversion has increased noticeably in the last decade.

Although we did not address the causes in our study, it seems likely that the driving forces for the types and increase in rate of land conversion are linked to growing international demand for products of New Zealand's high-value, more customised primary industries. In particular, land-based primary industries (dairying) have recently expanded and increased production nationally (MAF 2003). To enable estimates of the extent and location of future conversion, it may be helpful to identify the economic drivers of land conversion in the South Island more precisely, for example by modelling the economic structural process that underlies land-use changes (Veldkamp & Lambin 2001). Most case studies highlight the importance of policies in driving land use change (Lambin et al. 2001). The current spatial distribution of grassland conversion might also be better explained by modelling the underlying temporal dynamic processes and spatial interactions associated with economic agents (Irwin & Geoghegan 2001).

Incremental cumulative loss

While our study recorded recent loss of grasslands to intensive land use throughout our South Island study area, most of the change was found in three administrative districts: Waitaki, Mackenzie, and Central Otago. The most noticeable increases in the rate of conversion were in the Waitaki and Mackenzie districts, where the rate of land conversion doubled in the last decade. Most individual conversions were incremental and less than 140 ha in size, yet over the long term their cumulative effect was significant, particularly when combined with the few larger developments, such as the individual conversions of between 2000 and 5500 ha recorded in the Waitaki District.

In addition to loss of habitat for indigenous grassland species, an important cumulative effect of multiple incremental changes in land use and land management practices may be further fragmentation of the landscape, which in turn could be linked to changes in the attributes of biodiversity (Bascompte & Sole1996, Fahrig 2003, Weiner et al. 2011,). Small-scale conversions, along with the building of roads, fences, power lines and other infrastructure, provide opportunities for semi-natural vegetation to develop and form a network of corridors that facilitate dispersal of organisms, such as invasive exotic species, throughout the landscape. Such changes could lead not only to increased weed and pest invasion of remaining indigenous grasslands, but also to modification of ecosystem processes, including changes in decomposition rates, transfer of nutrients and soil erosion (Duncan et al. 2001, Wolters et al. 2000).

Our results suggest the scale of grassland conversion is such that the cumulative effects of land intensification on biodiversity loss and ecosystem services deserve greater attention in planning decisions under the Resource Management Act 1991 (RMA). At present, land clearance and other resource-use decisions associated with grassland conversion are usually assessed on a case-by-case basis (Heitzmann 2007). There may be a need to complement such decisions with regulatory limits, for example, that take into account the cumulative effects of land intensification on biodiversity loss and ecosystem services.

Need for increased protection

Despite substantial improvements in the reporting and analysis of grassland land conversion, there remains a major and widespread disparity between habitat loss and protection. The lack of protection of New Zealand's most threatened environments exemplifies this global trend. Recent grassland conversion is concentrated in environments that are poorly protected and with less than 30% of the total land environment remaining in indigenous cover. Though New Zealand has a much greater proportion of protected grasslands than most countries, there continues to be inadequate representation of the full range of indigenous grassland biodiversity (Mark et al. 2009) in the more threatened environments. The extent of remaining indigenous grasslands here still provides opportunity for New Zealand to make a major contribution to the conservation of global grassland biodiversity. Perhaps the best remaining opportunities to protect these grassland habitats exist where the government land reform (tenure review) process continues.

Acknowledgements

This paper was funded by The Miss E.L. Hellaby Indigenous Grassland Research Trust. Data were developed with support of Landcare Research. We particularly thank Jeromy Cuff (Environment Canterbury) for advice and technical support in the field. We also thank Hamish Heke, Anne Sutherland, Steven Campbell, and Janice Willoughby for their contributions toward the processing and compiling of satellite imagery and databases.

References

Barringer JRF, McNeill SJ, Pairman D 2002. Progress on assessing the accuracy of a high resolution digital elevation model for New Zealand. Proceedings, 5th International Symposium on Spatial Accuracy Assessment in Natural

Resources and Environmental Sciences, 10–12 July, Melbourne, Australia. Pp. 187–195.

Bascompte J, Sole RV 1996. Habitat fragmentation and extinction thresholds in spatially explicit models. Journal of Animal Ecology 65: 465–473.

Brower A 2008. Who owns the high country? The controversial story of tenure review in New Zealand. Nelson, Craig Potton. 199 p.

Congalton RG 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment 37: 35–46.

Duncan RP, Webster RJ, Jensen CA 2001. Declining plant species richness in the tussock grasslands of Canterbury and Otago, South Island, New Zealand. New Zealand Journal of Ecology 25(2): 35–47.

Dymond JR, Shepherd JD 2004. The spatial distribution of indigenous forest and its composition in the Wellington region, New Zealand, from ETM+ satellite imagery. Remote Sensing of Environment 90: 116–125.

Dymond JR, Shepherd JD, Qi J 2001. A simple physical model of vegetation reflectance for standardising optical satellite imagery. Remote Sensing of Environment 77: 229–239.

Dymond JR, Shepherd JD, Clark H, Litherland A 2006. Use of VEGETATION satellite imagery to map pasture quality for input to a methane budget of New Zealand. International Journal of Remote Sensing 27: 1261–1268.

Dymond JR, Shepherd JD, Arnold GC, Trotter CM 2008. Estimating area of forest change by random sampling of change strata mapped using satellite imagery. Forest Science 54: 475–480.

Ewers RM, Kliskey AD, Walker S, Rutledge D, Harding JS, Didham RK 2006. Past and future trajectories of forest loss in New Zealand. Biological Conservation 133: 312–325.

Fahrig, L 2002. Efect of habitat fragmentation on the extinction thrshold: a synthesis. Ecological Applications 12: 346–353.

Ferreira LG, Yoshioka H, Huete A, Sano EE 2003. Seasonal landscape and spectral vegetation index dynamics in the Brazilian Cerrado: An analysis within the Large-Scale Biosphere–Atmosphere Experiment in Amazônia (LBA). Remote Sensing of Environment 87: 534–550.

Gluckman P Sir 2011. Towards better use of evidence in policy formation: a discussion paper. Auckland, Office of the Prime Minister's Science Advisory Committee. 17 p.

Groombridge B ed. 1992. Global biodiversity: status of the earth's living resources : a report. 1st edn. Compiled by the World Conservation Monitoring Centre. New York, Chapman & Hall. 585 p.

Heitzmann M 2007. Lessons from the past and advice for the future. In: Beyond the RMA: an in-depth exploration of the Resource Management Act 1991. Conference proceedings, 30–31 May 2007. Auckland, Environmental Defense Society. Pp. 149–180.

Hewitt AE 1998. New Zealand soil classification. 2nd edn. Landcare Research Science Series 1. Lincoln, Manaaki Whenua Press. 133 p.

Irwin EG, Geoghegan J 2001. Theory, data, methods: developing spatially explicit economic models of land use change. Agriculture, Ecosystems & Environment 85: 7–24.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change 11: 261–269.

Leathwick JR 2001. New Zealand's potential forest pattern as predicted from current species-environment relationships. New Zealand Journal of Botany 39: 447–464.

Leathwick JR, Overton JMcC, McLeod M 2003. An environmental domain classification of New Zealand and its use as a tool for biodiversity management. Conservation Biology 17: 1612–1623.

Liu DS, Iverson LR, Brown S 1993. Rates and patterns of deforestation in the Philippines: application of geographic information system analysis. Forest Ecology and Management 57: 1–16.

MAF 2003. Contribution of the land-based primary industries to New Zealand's economic growth. Wellington, Ministry of Agriculture and Forestry. 54 p.

Mark AF, McLennan B 2005. The conservation status of New Zealand's indigenous grasslands. New Zealand Journal of Botany 43: 245–270.

Mark AF, Michel P, Dickinson KJM, McLennan B 2009. The conservation (protected area) status of New Zealand's indigenous grasslands: An update. New Zealand Journal of Botany 47: 53–60.

McAlpine KG, Wotton DM 2009. Conservation and the delivery of ecosystem services: a literature review. Science for Conservation 295. Wellington, Department of Conservation. 81 p.

McEwen WM 1987. Ecological regions and districts of New Zealand. 3rd rev. edn. Wellington, Department of Conservation.

McGlone MS 2001. The origin of the indigenous grasslands of southeastern South Island in relation to pre-human woody ecosystems. New Zealand Journal of Ecology 25(1): 1–15.

McWethy DB, Whitlock C, Wilmshurst JM, McGlone MS, Fromont M, Li X, Dieffenbacher-Krall A, Hobbs WO, Fritz SC, Cook ER 2010. Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. Proceedings of the National Academy of Sciences (USA) 107: 21343–21348.

Newsome PFJ 1987. The vegetative vover of New Zealand. Wellington, Water and Soil Directorate (MWD) for the National Water and Soil Conservation Authority. 153 p.

Newsome PFJ, Wilde RH, Willoughby EJ 2000. Land Resource Information System spatial data layers. Technical report. Palmerston North, Landcare Research. 74 p.

Ogden J, Basher L, McGlone M 1998. Fire, forest regeneration and links with early human habitation: Evidence from New Zealand. Annals of Botany 81: 687–696.

Pearson CJ, Ison RL 1997. Agronomy of grassland systems. 2nd edn. Cambridge University Press. 222 p.

Shepherd JD, Dymond JR 2003. Correcting satellite imagery for the variance of reflectance and illumination with topography. International Journal of Remote Sensing 24: 3503–3514.

Stevens G, McGlone M, McCulloch B 1988. Prehistoric New Zealand. Auckland, Heinemann Reed. 128 p.

Suttie JM, Reynolds SG, Batello C eds 2005. Grasslands of the world. Rome, FAO. 514 p.

Thompson S, Gruner I, Gapare N 2003. New Zealand Land Cover Database Version 2. Wellington, Ministry for the Environment.

Veldkamp A, Lambin EF 2001. Predicting land-use change. Agriculture Ecosystems & Environment 85: 1–6.

Walker S, Price R, Rutledge D, Stephens RTT, Lee WG

2006. Recent loss of indigenous cover in New Zealand. New Zealand Journal of Ecology 30: 169–177.
Walker S, Price R, Stephens RT 2008. An index of risk as a measure of biodiversity conservation achieved through land reform. Conservation Biology 22: 48–59.
Weiner CN, Werner M, Linsenmair KE, Blüthgen N 2011. Land use intensity in grasslands: changes in biodiversity, species composition and speacialisation in flower visitor networks. Basic and Applied Ecology 12: 292–299.
White R, Murray S, Rohweder M 2000. Pilot analysis of global ecosystems: grassland ecosystems. Washington, DC, World Resources Institute.
Wolters V, Silver WL, Bignell DE, Coleman DC, Lavelle P, van der Putten WH, De Ruiter P, Rusek J, Wall DH, Wardle DA, Brussaard L, Dangerfield JM, Brown VK, Giller KE, Hooper DU, Sala O, Tiedje J, Van Veen JA 2000. Effects of global changes on above- and belowground biodiversity in terrestrial ecosystems: implications for ecosystem

Editorial Board member: Peter Bellingham
Received 27 June 2011; accepted 26 March 2012

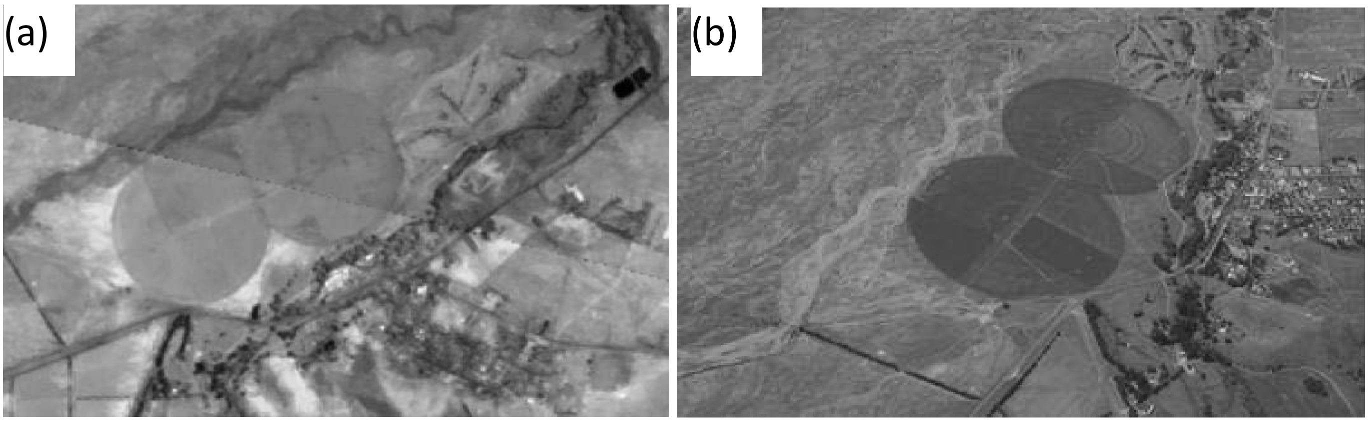
Appendix 1. Land cover classes used for the 1990 base map. Classes and descriptions adapted from Ecosat 1990 (Dymond & Shepherd 2004) and New Zealand Land Resource Information (NZLRI) (Newsome et al. 2000).

Land cover	Class	Description
Forest	Indigenous forest	Tall or short forest (>30% cover)
	Planted forest	Radiata pine, Douglas-fir, eucalypts, or other planted forestry tree species
		Roads/tracks within forest area
		Invasive exotic trees
		Shelterbelts
Grassland	Non-indigenous grassland	Grassland dominated by exotic species (*Lolium*, *Trifolium* and *Agrostis* species)
	Indigenous grassland	Low-fertility grasses on hill country
		Grasslands dominated by indigenous species (*Festuca*, *Poa* and *Chionochloa* species)
Cropland	Cropland-perennial	Orchards
		Vineyards
	Cropland-annual crops	All annual crops
		Cultivated bare ground
Settlements	Settlements	Built-up areas and impervious surfaces
Bare ground	Other land cover	Montane rock/scree
		Largely bare soil (if not cropland)
		Roads
		Open-pit mines
		Any other remaining land
Water	Open water	Rivers, riverbeds, streams, ponds, natural lakes
		Man-made lakes and reservoirs
Shrubland	Native or exotic shrub	Broadleaved hardwood shrubland, mānuka/kānuka shrubland, and other woody shrubland (>30% cover)
		Matagouri and sweet briar
Wetland	Vegetated non-forest	Herbaceous and/or non-forest woody vegetation: periodically flooded
		Estuarine/tidal areas

Appendix 2. Description of non-indigenous land cover types.

Land cover type	Sub-type	Description
Afforestation	Planted forest	Radiata pine, Douglas-fir or other planted forestry species
	Invasive exotic forest	Wilding (not intentionally planted), radiata pine, Douglas-fir, or other forestry tree species
Agriculture	Exotic pasture	Grasslands with non-indigenous species (rye grass, clover, brown top, sweet vernal, Timothy, Yorkshire fog)
	Cropland	Perennial and annual crops including cultivated bare ground
Barren land	Settlement	Built-up areas and impervious surfaces; grasslands with settlements including recreational areas
	Open-pit mining	Open-pit mining

Appendix 3. Example of oblique aerial photographs used to confirm mapped land-use classifications: (a) SPOT-5 imagery taken in the summer of 2007/08 (10-m resolution), using band combinations XS3, SWIR, and XS2 to show the spectral signature of an irrigated pasture, and (b) corresponding oblique photo taken in the summer of 2009 at 2000 m above sea level, using a Canon A640 7.1 megapixel compact camera. Image (a) shows high-productivity 'exotic pasture' (orange-red colour) readily distinguishable from lower-productivity 'indigenous grassland' (aqua blue) and bare soil (light blue). Image (b) shows the corresponding natural colours.



Appendix 4. Threatened Environment categories and descriptions adapted from Walker et al. (2006, table 1).

Category	Criteria	Category name
1	<10% indigenous cover left	Acutely Threatened
2	10–20% left	Chronically Threatened
3	20–30% left	At Risk
4	>30% left and <10% protected	Critically Underprotected
5	>30% left and 10–20% protected	Underprotected
6	>30% left and >20% protected	Less reduced and better protected