

Chapter 2. Temporal changes in patch and infestation dimensions

“Weeds deal with ecological emergencies. When the emergencies are over, they give way ... and they will usually die out if disturbance ceases ... Weeds thrive on radical change, not stability.”

Alfred W. Crosby, 1986, *Ecological Imperialism. The Biological Expansion of Europe, 900-1900*, Cambridge University Press, Cambridge, UK, pp. 169-171.

Summary

This chapter details rates of change in *N. neesiana* infestation dimensions determined from comparison of historical and modern aerial photography and field measurements over periods of two to six years, and relates these changes to what is known of the contemporaneous disturbance and management regimes. The data indicates that *N. neesiana* patch margins tended to be stable where they abutted healthy, well-managed grasslands, which appear to be resistant to invasion. Patches expanded into disturbed areas and grassland in poor ecological condition at rates that exceeded 1 m per year. The most rapid expansion rates occurred in areas with senescence dieback of *T. triandra*, where patch areas often expanded by more 20% per year, and on roadsides that were frequently mown short, where linear expansion rates >5 m per year were measured. Data from Laverton North Grassland suggests that management by fire may contain or reduce infestations. The dynamics of *N. neesiana* infestations appear to support the theory of an alternative stable state in native grasslands that requires powerful intervention to shift, and indicate that expansion of infestations is driven by inappropriate management regimes.

Introduction

A critical variable determining the overall biodiversity impact of *N. neesiana* is the extent and rates of change of its land cover. However worldwide knowledge about vegetation cover in general is poor and there is a paucity of accurate data, particularly in relation to dynamics (Foody 2002). Vegetation maps rarely depict cover at the scale of interest for most invasive plants and usually at best portray vegetation at the plant community level.

There is a long history of the use of aerial photography and remote sensing in vegetation mapping and weed detection (e.g. Field *et al.* 1993). Several studies have used remote sensing techniques including aerial photography and satellite imagery to determine spread of

invasive plants (Byers *et al.* 2002). Chan (1980) was able to map the distribution of grassland types in the Australian Capital Territory using low altitude colour aerial photography. He distinguished eight major grassland types but ignored areas dominated by exotic grasses. Dominant native grass species were determined by colour and texture. *Themeda triandra* and *Bothriochloa macra* were best identified by distinctive colour in autumn, with the latter having a finer, denser texture. Improved pastures and weedy areas were intensely green. Inspection of more recent, small scale, aerial photographs of Canberra demonstrated that *N. neesiana* patches identified on the ground could clearly be distinguished in photographs taken at an appropriate season. It therefore appeared feasible to determine historical changes in infestation dimensions by interpretation of appropriately selected photographs or satellite imagery, in conjunction with ground inspections.

No published data appear to be available on the land cover of *N. neesiana* in Australia at scales other than the local, 'individual grassland' scale, and the maps that exist have limited utility. Rowell (1996), for instance, described the process by which detailed maps of the dominant grass types were prepared for Yarramundi Reach. Ground examination in 10 x 10 m grid cells produced useful maps that included a few cells dominated by *N. neesiana*. Bruce (2001) prepared hand drawn sketch maps of Canberra grasslands showing the extent of *N. neesiana* infestations but these were not part of her actual report. Muyt (2005) estimated the cover/abundance of *N. neesiana* and other major grasses in a grid of 50 x 50 m contiguous cells across the whole of Yarramundi Reach grassland but failed to convert the data to map form. The reported studies are temporally static pictures, difficult to replicate and more or less incommensurable. Yarramundi Reach nevertheless appears exceptional in regard to available studies; if such information exists for other grasslands it is not readily available and would usually be subject to considerable uncertainty due to the absence of contemporary mapping of deliberate control activities targeted at the weed.

The dynamics of *N. neesiana* infestations are poorly understood. The best available data are from New Zealand, where a maximum rate of dispersal on a linear front from known sources was 8 km in 59 years at Marlborough and 3.5 km in 30 years at Waipawa (Connor *et al.* 1993). Slay (2002a 2002c) also provided expansion rate information for New Zealand infestations (Table 2.1).

Similar measurements and estimates are not available for *N. neesiana* in Australia. The ACT Weeds Working Group (2002 p. 4) stated that the "rate of spread and establishment is unknown, but believed to be rapid". *Nassella neesiana* was rated by Platt *et al.* (2005) as having a rapid, rather than a moderate or slow 'rate of dispersal'. The widespread perception that there has been rapid spread in Australia has probably been partly conditioned by recognition failures (Walsh 1998): the date of first establishment at a site has rarely been

determined with any accuracy, and infestations may have grown large over many years before the plant was first identified.

Estimates of rates of spread are required at a range of scales. At the regional scale, rare long distance dispersal events are likely to be an important factor. A small number of widely separated new infestations at the regional scale rapidly expand the plant's range. At the district scale infestations are known to expand first along linear corridors and within properties etc., strongly influenced by human land use, landscape boundaries and other anthropic factors such as mowing. In native grasslands at the local and patch scales, the interaction of the management regime and the integrity of the existing natural vegetation determine the fate of *N. neesiana* propagules and the fate of existing plants.

Table 2.1. Measured and inferred rates of *N. neesiana* spread in New Zealand.

Locality	Distance (m)	Period (y)	Rate of spread (m y^{-1})	Notes	Reference
Marlborough	8000	59	136	District infestation expansion	Connor <i>et al.</i> 1993
Waipawa	3500	30	117	District infestation expansion	Connor <i>et al.</i> 1993
New Zealand			120-140	With no active management	Slay 2002c
Hawke's Bay	3-10	5	0.6-2	Patch expansion	Slay 2002c
	Area (ha)		(ha y^{-1})		
Marlborough	1555-3000 (3071)	14-15	101-103	District expansion	Slay 2002a, 2002c
hypothetical	1	5	100	Expansion at 100 m per year	Slay 2002a
hypothetical	1	10	350	Expansion at 100 m per year	Slay 2002a

This chapter examines temporal changes in the dimensions of patches and local infestations at selected sites for which long-term information is available, and their relationship to grassland management regimes. An unsupervised visual classification based on relative spectral and textural similarity of 1 m scale image areas was used to determine historical infestation boundaries. Ground inspections and measurements were used to locate and determine the current dimensions of *N. neesiana* patches and their locations. These data were then used to estimate rates of change in infestation areas and the movement of infestation margins over periods of two to six years. Ground inspections enabled subjective assessment of the qualities of the matrix vegetation and disturbance regimes, and this information was supplemented by records of historical management regimes and interpretation of older aerial photography to identify factors influencing vegetation composition. Judgements were then made of the effects of disturbance and management factors on the ability of the native vegetation to resist invasion and the factors important in determining rates of spread of *N. neesiana*.

Methods

Rates of change in the size of *N. neesiana* infestations and patches were assessed by examination of historical and recent aerial imagery and comparison of current on-ground measurements. Photographs were obtained from government photograph libraries and archives, a commercial supplier of remote sensing imagery, and from Google® Earth (©Digital Globe). Areas of *N. neesiana* patches measured on the ground at Crace, Yarramundi Reach, Dudley Street and Laverton North grassland reserves were compared with areas interpreted from scanned, re-scaled and digitally manipulated historical images. Changes in the areas of dense *N. neesiana* infestations and linear expansion at patch boundaries were calculated over time, and rates of change were estimated. Rates of change at a particular site were estimated by comparison of one image with another, and/or by comparison of data derived from images with measurements taken in the field.

Ground measurements and verification

The positions of prominent and distinct infestations of *N. neesiana* located in on-ground studies were recorded with a GPS device and by measuring their distances from prominent landmarks using a surveyor's tape and magnetic compass. Some additional patches were initially located from the remote imagery and their positions determined in the same way. The area of each patch inspected on the ground was determined by measuring a series of radii from the nominal patch centre using a surveyor's tape. The compass direction of each radius was determined with a magnetic compass. A hand drawn sketch of the patch indicated patch boundary features between the outer ends of the measured radii. These data were plotted on graph paper and the approximate area of each patch was calculated manually.

Image analysis

Historical aerial photographs and satellite images obtained on paper were manipulated and re-scaled using a high resolution flatbed scanner, photocopier and image processing software. Images obtained in electronic form were subsampled and manipulated with the same software. Image manipulation mainly involved alteration of colour and contrast using widely available photo editing software products.

Known *N. neesiana* infestations were located on recent photographs by field examination, and additional infestations were identified by their similarity of appearance to the known infestations on the photographs, including spectral and textural characteristics. Late spring and summer photographs were found to provide the best delineation of infestations. Patches were progressively more difficult to delineate in the older, lower resolution images and in old grey-scale photographs. Colour and texture contrasts often enabled ready identification of the dominant native grass *T. triandra* when photos were taken at the appropriate time of year (autumn being best), and uniform swards of other major grasses could also be identified

with some certainty after ground-truthing. In general *T. triandra* appears reddish or pinkish and greenish blue, whereas *N. neesiana* often has a pronounced yellowish tinge or is a strong straw yellow colour where mown on roadsides, after the flowering period.

Various difficulties were encountered in interpreting the remotely sensed images. Most important was the low resolution of some images at the scale of interest. Diffuse patch boundaries and intermixtures of *N. neesiana* with other grass species complicated interpretation. Images at the optimum time of year for clear delineation of *N. neesiana* infestations were rarely available. The optimum times of year for identification of other grasses making up the invaded matrix were usually different to that of *N. neesiana*.

Infestations can change their apparent size and shape on remotely sensed images due to parallax errors which are most severe when the area of interest is remote from the centre of the image and when infestations are small. Parallax errors are an inevitable consequence of using photographs from different series. The interaction of slope and variation in camera angles also influences the accuracy of positional and area data obtained from photographs. No attempt was made to account for or quantify such errors. Alterations of apparent size and shape of patches without corresponding change in the number or density of plants also results from varying seasonal growth patterns and responses to rainfall of *N. neesiana* and other dominant grasses, the effects of grazing, fire, etc. A small narrow infestation at the peak of the growth period in a good season might appear much larger than the same infestation during a drought period when foliar cover is much reduced. Errors from such variation were also not accounted for, although they would be minimal at large patch size.

Approximate boundaries of infestations on historical images were determined by comparison of fine scale colour and textural properties of known *N. neesiana* infestations with those of the matrix (usually *T. triandra*) vegetation. An area was considered part of the matrix if it was more similar to the matrix vegetation in that particular area of the image than it was to the *N. neesiana* infestation in that area of the image. Factors affecting image interpretation included variations in image quality due to atmospheric influences (e.g. cloud), in image definition due to shading (by clouds or adjacent trees) and other effects, and fine scale variation in grass cover, density and height, along with other grassland compositional parameters (e.g. admixture of other species). Such variations were subjectively 'smoothed', avoiding the complications inherent in algorithmic approaches that accommodate such fine scale variation only with difficulty (Foody 2002). The boundaries of infestations were traced and their areas were manually calculated using graph paper.

The approaches used to measure changes in infestation dimensions at each grassland varied depending on the opportunities presented in the range of aerial images available and the extent of previous on-ground studies. The Dudley Street grassland was small, with an

intensively mown roadside verge and very well defined major intrusion of *N. neesiana* bounded by healthy *T. triandra* grassland. Assessments were therefore undertaken of the overall change in the area of *N. neesiana* dominated grassland over a broad, partially infested area (>3 ha), of the linear change in the road verge infestations and the edges of other infestations, and of the change in area and boundary positions of the prominent *N. neesiana* intrusion. Yarramundi Reach exhibited numerous discrete *N. neesiana* patches. The absence or infrequency of biomass reduction management over a long period at this grassland meant that these could be readily identified by their high contrast in historical photographs. At Crace only a single *N. neesiana* 'patch' and the wider infestation of which it was a part were assessed. Other patches identified at Crace were generally very small and grazed close to the ground so were difficult to identify in aerial images. At Laverton North many patches identified on the ground were too small and diffuse to be clearly delineated on the aerial images, so some additional discrete patches, prominent in the imagery, were investigated and measured.

Results

Dudley Street grassland, Yarralumla, ACT

Stands of other exotic grasses at the site included *Paspalum dilatatum* and smaller areas of *Festuca arundinacea* Schreb. *Paspalum dilatatum* plants were largely restricted to wetter hollows in 2007 and could generally be readily distinguished from *N. neesiana* and *T. triandra* in aerial photographs, but the *F. arundinacea*, although largely confined to the roadside, was difficult to distinguish from *N. neesiana*. Tall rank grasses, notably *Avena* sp. and *Bromus* sp. occurred at shaded (southern) edges of major exotic tree plantations in 2007. These too were difficult to distinguish from *N. neesiana* in aerial photographs.

Arbitrary boundaries were set on the broad section of grassland in which the area of *N. neesiana* infestation was calculated (Fig. 2.1). These were defined by the edge of Dudley Street and extended approximately 122 m to the north and 260 m east-west, giving a total assessed area of c. 31,720 m² (Fig. 2.1). Some of this area (c. 35%) was covered by the exotic tree plantations which are not suitable habitat for *N. neesiana*.

The rate of expansion of the *N. neesiana* infestations in this broad section of the grassland to 2001 (Table 2.2) was calculated over 6 years using an arbitrary date of initial infestation of 31 March 1995. This very approximate estimate was based on Berry and Mulvaney (1995 Vol. 2 Appendices p. 261), who recorded that *N. neesiana* was common at that time along the bicycle path at Yarramundi Reach grassland, c. 2.8 km to the north west of the Dudley Street grassland. A part of the Canberra path network used by cyclists passes across the northern side of the Dudley Street reserve, so *N. neesiana* might have been present at Dudley

Street or dispersed there in that year. If it did, an average rate of expansion of c. $1000 \text{ m}^2 \text{ y}^{-1}$ occurred in the 6 years to 2001 (Table 2.2). The first ACT record of *N. neesiana* dates from 1960 (Gardener 1998) and Vickery *et al.* (1986) listed four ACT localities for the species. If in 2001 *N. neesiana* had been present at this grassland for 41 years the average rate of expansion in this grassland reserve to March 2001 would have been c. $158 \text{ m}^2 \text{ y}^{-1}$. The average annual rate of expansion from 2001 to 2005, calculated on the basis of 3.81 years between photographs, was c. 9% or c. $550 \text{ m}^2 \text{ yr}^{-1}$ (Table 2.2).



Figure 2.1. Dudley Street grassland, ACT, 21 January 2005, showing the broad area of grassland (pale) and exotic plantation trees (black) assessed for *N. neesiana* areal cover (red line), the *N. neesiana* intrusion ('patch', red arrow) upon which estimates of rates of change of area and linear boundary changes were made, and the roadside infestations (green arrows) assessed for linear expansion rates. Pale, yellowish areas are *N. neesiana*; purplish green areas are *T. triandra*.

Table 2.2. Areal extent of *N. neesiana* infestation, proportion of total area infested and calculated rates of expansion of infestations at Dudley Street grassland 1995-2005, based on air photo interpretation.

Date	Area (m ²)	Proportion of total area infested (%)	Rate of expansion (m ² year ⁻¹)	Rate of expansion (% year ⁻¹)	Source (literature or aerial photograph)
31/3/95	0	0	-	-	Nominal time of first infestation (Berry and Mulvaney 1995)
31/3/01	6220	19.6	1037	-	Canberra 2001 NSW4548(M2261) Run 5 31-3-01 41-62 Land and Property Information
21/1/05	8300	26.2	546	8.8	Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands

A comparison was made of the area of a large *N. neesiana* patch at 35°18.844' 149°05.490' (Figs. 2.1, 2.2) that was measured on the ground on 14 October 2007 using a surveyor's tape and magnetic compass, and the area of this patch assessed from interpretation of the 2001 and 2005 aerial photographs (Table 2.3). In October 2007 the eastern, southern and western edges of the patch had been sprayed with herbicide and the *N. neesiana* in the sprayed band was dead. The core area ("inner zone") of living *N. neesiana* measured on the ground was substantially less than that estimated from the more recent aerial photograph; however a modest expansion (+2%) was measured if the sprayed band was included. Ground inspections elsewhere at this site in October 2007 revealed that active *N. neesiana* invasion was clearly continuing in some areas where *T. triandra* was senescing.

Table 2.3. Areas of *N. neesiana* patch at 35°18.844' 149°05.490' at Dudley Street compared by field measurement on 14 October 2007 and from interpretation of aerial photographs of 31 March 2001 (Canberra 2001 NSW4548(M2261) Run 5 31-3-01 41-62 Land and Property Information) and 21 January 2005 (Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands). Rates of change were calculated based on periods of 6.54 years between the 2001 photograph and the ground measurement, and of 2.73 years between the 2005 photograph and the ground measurement.

Area 2001 photo (m ²)	Area 2005 photo (m ²)	Area 2007 ground measurement (m ²)	% change 2001-2007	% change 2005-2007	Rate of change of patch area 2001-2007 (m ² year ⁻¹)	Rate of change of patch area 2005-2007 (m ² year ⁻¹)
462	660	540 (inner zone)	+17	-26	+ 12	- 44
462	660	674 (including area sprayed out)	+46	+2	+ 32	+ 5

The area of the patch was also estimated from images available on Google Earth (Table 2.4). Nine images were available over the period from 22 December 2002 to 31 March 2008. The resolution of these images was generally poor, with pronounced pixilation at the scale of interest, but of similar quality to the aerial photography previously assessed, except for the 31 March 2008 image, which has extraordinarily high resolution (Fig. 2.2b). Google Earth provides an onscreen scale that readily enables area calculations.

The earliest of these images (2002) indicates a roughly crescent-shaped infestation with a large central inclusion, apparently of *T. triandra*. Subsequent images show a gradual extension and widening of the arms of the crescent, and the concurrent decrease in the size of the central inclusion until the arms were almost joined in 2005 (Fig. 2.2a). By February 2006 the central inclusion had become isolated and smaller. No inclusion was obvious when the patch was examined in the field in 2007 and by March 2008 no remnant *T. triandra* was evident in the aerial view (Fig. 2.2 b). During the expansion phase, finger-like projections appeared to extend downhill from the south-expanding edge of the patch, following what would appear to be drainage lines.

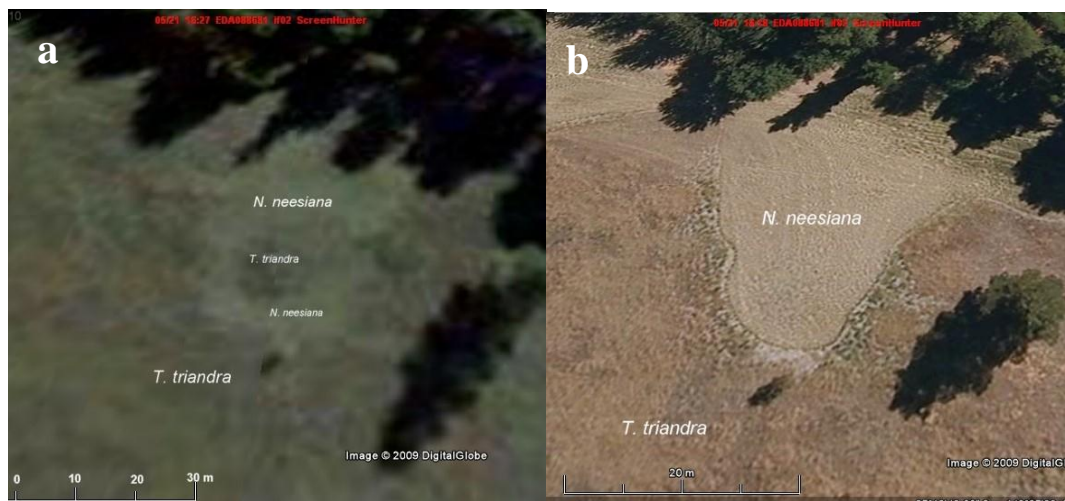


Figure 2.2. *Nassella neesiana* patch at Dudley Street, ACT. a. 19 April 2005, showing a central inclusion of *T. triandra*; b. 31 March 2008, with the central inclusion of *T. triandra* completely replaced by *N. neesiana*, and relatively stable margins abutting healthy *T. triandra* grassland to the east, south and west, as well as a distinct line around the patch indicating a narrow zone where the outer edge of the *N. neesiana* was chemically controlled.

During the period of 3 years from 22 December 2002 to 12 December 2005 the *N. neesiana* patch is estimated to have expanded by an average of $84 \text{ m}^2 \text{ y}^{-1}$ or $32\% \text{ y}^{-1}$ (Table 2.4). During the subsequent period of 2.3 years from 12 December 2005 to 31 March 2008 the patch expanded an average $338 \text{ m}^2 \text{ y}^{-1}$ or c $130\% \text{ y}^{-1}$. Over this whole period of 6.41 years

the patch expanded on average by 195 m² y⁻¹ or 75% y⁻¹. The area of the patch approximately doubled in the 3 years from 2002 to 2005 and then doubled again in the next 3 years. The central inclusion of *T. triandra* shrunk by an average of c. 20% y⁻¹ over this total period.

Table 2.4. Progressive change in area of *N. neesiana* patch at 35°18.844' 149°05.490' at Dudley Street 2002-2008 by interpretation of Google Earth images. A central inclusion of native grass within this patch apparently degraded slowly from dense *T. triandra* to sparse *T. triandra* invaded by *N. neesiana* to more or less pure *N. neesiana* over this period. The 31 March 2008 data includes two patch sizes defined by the inner and outer margins of a herbicidal kill zone intended to limit patch expansion. Calculations in square brackets for two images only 18 days apart are clearly unrealistic and indicative of the difficulties of determining patch boundaries from low resolution imagery.

Date	Patch area without central inclusion (m ²)	Area of central <i>T. triandra</i> inclusion (m ²)	Period between images (years)	Rate of change of patch area (m ² year ⁻¹)	Rate of change of patch area (% year ⁻¹)	Rate of change of central inclusion area (m ² year ⁻¹)	Rate of change of central inclusion area (% year ⁻¹)
Changes from preceding image							
22/12/02	260	220	–	–	–	–	–
11/3/04	353	371	1.22	+76	+29	+124	+56
29/3/04	340	330	0.05	[-260]	[-74]	[-820]	[-221]
19/3/05	400	206	1.06	+57	+17	-117	-36
12/12/05	510	189	0.65	+169	+42	-26	-13
22/2/06	521	113	0.20	+55	+11	[-380]	[-201]
9/10/06	573	124	0.63	+83	+16	+18	+16
2/4/07	797	68	0.48	+467	+81	-117	-94
31/3/08 inner	1044	0	1.00	+247	+31	-68	-100
31/3/08 inner + outer	1288	0	1.00	+491	+62	-68	-100
Changes over longer periods							
22/12/02-12/12/05	–	–	2.97	+84	+32	-10	-5
12/12/05-31/3/08 (inner)	–	–	2.30	+338	+66	-82	-44
22/12/02-31/3/08 (inner)	–	–	5.27	+195	+75	-42	-19

Linear change in infestations was estimated by: a. comparison of one aerial photograph with the other, or by comparison of an aerial photograph with measurements taken in the field from prominent landmarks including the road gutter and a large pine tree (Table 2.5); and b. comparison of distances measured in successive Google Earth images (Table 2.6).

Table 2.5. Linear expansion of *N. neesiana* infestations at Dudley Street grassland 2001-2005 based on aerial photography and field measurements.

Date	Infested area	Linear expansion (m)	Period (years)	Rate of linear expansion (m year ⁻¹)	Source (aerial photographs, field measurement)
31/3/01-21/1/05	eastern roadside	19.6-21.8	3.81	5.1-5.7	Canberra 2001 NSW4548(M2261) Run 5, 31-3-01, 41-62 Land and Property Information; Canberra 1:25000 NSW4889 (M2460) Run 8, 21-1-05, 26-50 Department of Lands
31/3/01-21/1/05	western roadside	28.4	3.81	7.5	Canberra 2001 NSW4548(M2261) Run 5, 31-3-01, 41-62 Land and Property Information; Canberra 1:25000 NSW4889 (M2460) Run 8, 21-1-05, 26-50 Department of Lands
31/3/01-21/1/05	core areas	0-33	3.81	0-8.7	Canberra 2001 NSW4548(M2261) Run 5, 31-3-01, 41-62 Land and Property Information; Canberra 1:25000 NSW4889 (M2460) Run 8, 21-1-05, 26-50 Department of Lands
21/1/05-14/10/07	35°18.844' 149°05.490' E-W diameter, inner zone	0.9	2.73	0.3	Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands; field measurement 14/10/07
21/1/05-14/10/07	35°18.844' 149°05.490' E-W diameter, incl. sprayed zone	3.6	2.73	1.3	Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands; field measurement 14/10/07

Table 2.6. East-west diameter and distance north from road of the Dudley Street *N. neesiana* patch from Google Earth imagery 2002-2008. Rates of change for the east-west diameter were calculated as half the change in diameter, assuming patch margin movement occurred on both east and west sides of the patch.

Date	East-west diameter of <i>N. neesiana</i> patch (m)	Distance from road edge to south margin of patch (m)	Period between images (years)	Rate of linear expansion, east-west (m year ⁻¹)	Rate of linear expansion south (m year ⁻¹)
22/12/02	27.3	79.1	-	-	-
11/3/04	25.0	78.4	1.22	0.94	0.57
19/4/05	29.6	75.0	1.11	2.07	3.06
12/12/05	30.2	76.2	0.65	0.46	-1.85
22/2/06	34.6	79.5	0.20	11.00	-16.5
9/10/06	35.2	79.1	0.63	0.48	0.64
2/4/07	38.6	79.1	0.48	3.54	0.00
31/3/08	39.1	80.1	1.00	0.25	1.00
22/12/02-31/3/08			5.27	1.12	0.19

Linear expansion appeared to be most rapid along mown road verges (5-7.5 m y⁻¹), but similar rapid expansions of up to 8.7 m y⁻¹ were apparent in some of the core areas of the grassland (Table 2.5). Other infestation margins remained stable over the period. Google Earth images showed a consistent expansion trend in the east-west diameter of the measured patch, but a fluctuating expansion and contraction in the southern margin of the patch (Table

2.6). On average over the period of assessment the patch expanded by c. 1 m on each of the east and west margins and only slightly to the south. Field observations in 2007-2008 indicated that southward expansion was limited by healthy, non-senescent *T. triandra* and westerly expansion occurred into senescent *T. triandra*.

Expansion of the infestations appears to have been driven by two main management factors, mowing of the *N. neesiana* areas with their remnant tussocks of native grasses, and senescence of *T. triandra* in unmown areas. Mowing close to the ground appears to have accelerated the disappearance of *T. triandra*. When mown, *N. neesiana* is able to produce new tillers that grow near horizontally (City of Whittlesea, no date; direct observations at Yarramundi Reach bicycle path), so is able to prosper in lawns. *T. triandra* lacks such flexibility. Mowing too close to the ground appears to remove the meristematic tissue of *T. triandra* and kills larger tussocks. Mowing also increases the amount and distance of seed dispersal of *N. neesiana*. These factors are discussed in more detail below.

Illustrative of these points, a severe circular scar caused by deep vehicle tyre marks in the core of the healthy *T. triandra* at Dudley Street grassland, that appeared fresh in October 2006, had by 13 October 2007 been occupied by *T. triandra* and *Austrodanthonia* seedlings. Although connected to the roadside, the scarring was apparently sufficiently distant from *N. neesiana* seed sources to preclude invasion.

Yarramundi Reach, ACT

Assessments were made of the change in size of several patches over different periods (Table 2.7). Calculated patch sizes from 2007 or 2008 ground measurements were compared to patch sizes estimated from the 21 January 2005 aerial photograph (Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands). The periods from the time of the aerial photograph to those of the ground measurements were 2.34 years to 25 and 26 May 2007, 2.72 years to 11 and 12 October 2007, 2.74 years to 17-19 October 2007 and 3.75 years to 21-23 October 2008.

Large areas of *Phalaris aquatica* were present at this grassland, but these were relatively easy to distinguish on the images. *Festuca arundinacea* was present in significant stands, sometimes intermixed with *N. neesiana*, and may have been confused with *N. neesiana* in the photo interpretation. Nevertheless it is certain that major rapid expansion of the size of *N. neesiana* patches occurred over the period. All patches were assessed to have increased in size. One doubled in size annually, while several had annual rates of areal increase of 30-70%. There is some indication that larger patches expanded at a proportionally greater rate (Table 2.7).

The main factor driving patch expansion at this grassland over the period appeared to be senescence of *Themeda triandra*. Senescent stands were prevalent throughout the area (Fig.

2.3). There were large areas where *T. triandra* was evidently dying. Where dieback was not occurring, the stands still frequently had extremely high foliar cover (>90%) with a high proportion of dead leaves. Small areas of healthy *T. triandra* occurred in upslope areas in the far south-west of the grassland, and in infrequently mown zones around buildings, along some edges of the grassland and along small sections of the bicycle track. The data indicate that critical levels of *T. triandra* senescence occurred over the period, resulting in very rapid increase in the areal extent and density of *N. neesiana*.



Fig. 2.3. Yarramundi Reach *N. neesiana* Patch R, looking approximately east, with Lake Burley Griffin in the background, 24 October 2008. The patch was bounded to the east and north by highly senescent *T. triandra*. In the foreground *N. neesiana* was invading senesced *T. triandra*. The area of the patch is estimated to have expanded by 13% per year in the period from January 2005 until October 2008.

Table 2.7. Comparison of the size of *N. neesiana* patches at Yarramundi Reach grassland assessed by ground measurement and interpretation of 21 January 2005 aerial photograph (Canberra 1:25000 NSW4889 (M2460) Run 8 21-1-05 26-50 Department of Lands), with calculated proportional change over the periods and annual rates of change.

Patch	Location	Ground assessment		Air photograph 21/1/05		% change in area	Period (years)	% change per year
		Area (m ²)	Date	Area (m ²)	Comments			
		a		b		c	d	
A	35°17.367' 149°05.047'	369	25/05/07	160	Partially obscured by tree shadows	+131	2.34	+56
D	35°17.443' 149°04.812'	225	11/10/07	110	Boundaries unclear	+105	2.72	+39
C	35°17.501' 149°04.897'	156	26/05/07	43		+263	2.34	+112
G	35°17.382' 149°05.017'	128	24/10/08	73		+75	3.75	+20
P	35°17.426' 149°04.890'	121	21/10/08	81	Possibly more extensive – S end obscured by mown zone	+49	3.75	+13
B	35°17.453' 149°04.933'	120	25/05/07	94		+28	2.34	+12
E	35°17.430' 149°04.955'	103	12/10/07	35	In two sections, 19.0 & 16.5 m ²	+194	2.72	+71
Q	35°17.336' 149°05.014'	95	23/10/08	31	Patch unclear, ?in two sections 15.0 & 15.9 m ²	+206	3.75	+55
O	35°17.338' 149°05.008'	94	19/10/07	?	Patch not apparent - in mown zone	-	2.74	-
H	35°17.432' 149°04.886'	80	17/10/07	?	Patch not apparent - in mown zone	-	2.74	-
F	35°17.439' 149°04.947'	77	12/10/07	46	In two sections, 18.3 & 27.5 m ²	+67	2.72	+25
R	35°17.326' 149°05.031'	75	24/10/08	51		+47	3.75	+13
N	35°17.337' 149°05.064'	60	19/10/07	27		+122	2.74	+45
D ext	35°17.448' 149°04.812'	54	11/10/07	21	Boundaries unclear	+157	2.72	+58
M	35°17.375' 149°05.031'	32	19/10/07	14		+129	2.74	+47
K	35°17.451' 149°04.835'	16	18/10/07	8		+100	2.74	+37
L	35°17.528' 149°04.842'	15	18/10/07	8	Small patch, location unclear	+88	2.74	+32
I	35°17.512' 149°04.911'	12	17/10/07	9	Small patch, not certainly identifiable	+33	2.74	+12
J	35°17.509' 149°04.904'	12	17/10/07	7	Small patch, not clearly discernible	+71	2.74	+26

Crace Grassland Reserve, ACT

Six Google Earth images covering the period from December 2002 to March 2008 were interpreted for an *N. neesiana* infestation at 35°13.693' 149°07.378' at Crace (Tables 2.8, 2.9). A number of available images including December 2005 were excluded due to their lack of clarity. The infestation was defined on its northern side by an old fence line and appears to have arisen as a result of overgrazing by rabbits and livestock, probably very similar to the sort of degradation illustrated in Figs. 2.4 and 2.5.

The area of the infestation, which had some very diffuse margins, was roughly measured on the ground on 16 October 2007 and the area of a well-defined section, Patch A, was measured more precisely (Table 2.8). The area of the patch and the wider infestation as interpreted on the ground differed substantially from that interpreted from remote sensing. During the longer period from 2002 to 2008 (Table 2.9) the infestation appears to have fluctuated in size and perhaps increased slightly in area. Overall, the patch and infestation data for this grassland suggest relative stability of *N. neesiana* areas under the regime of intense grazing.

Table 2.8. Area of *N. neesiana* infestation and incorporated Patch A at Crace Grassland, assessed by on ground measurement and interpretation of Google Earth imagery.

	Area (m ²)			% change		
	16/10/07 ground	2/4/07 image	31/3/08 image	16/10/07- 2/4/07	16/10/07- 31/3/08	2/4/07- 31/3/08
Infestation	384	572	599	+49	+56	+5
Patch A	210	148	185	-30	-12	+25

Table 2.9. Progressive change in area of *N. neesiana* infestation around patch A at Crace Grassland Reserve 2002-2008 by interpretation of Google Earth images.

Date	Infestation area (m ²)	Period between images (years)	Rate of change of patch area (m ² y ⁻¹)	Rate of change of patch area (% y ⁻¹)
Changes from preceding image				
22/12/02	554	–	–	–
11/3/04	492	1.22	-51	-9
9/4/05	507	1.08	+14	+3
22/2/06	409	0.87	-113	-2
2/4/07	572	1.02	+160	+39
31/3/08	599	1.01	+27	+5
Changes over longer periods				
22/12/02-9/4/05	–	2.30	-20	-4
9/4/05-31/3/08	–	2.97	+31	+6
22/12/02-31/3/ 2008	–	5.27	+9	+2



Figure 2.4. Western side of Crace Grassland Reserve, looking west, 8 May 2007, showing a dense monoculture of *N. neesiana* within the fence of the building compound and a belt of green *N. neesiana* in a drainage line leading downhill from the compound, grazed very short by rabbits.



Figure 2.5. Elevated area in the north-west section of Crace Grassland Reserve, looking south-west towards the Barton Highway with the Black Mountain tower in the background, 8 May 2007. The area in the foreground had been highly disturbed by cattle and kangaroo grazing and was densely infested with *N. neesiana*.

Table 2.10. Comparison of the size of *N. neesiana* patches at Laverton North Grassland assessed by ground measurements and interpretation of 24 January 2006 aerial photograph (2006 City of Wyndham Project, Wyndham_2006Jan24_air_vis_15cm_mg55.ecw), with calculated proportional change over the periods and annual rates of change.

Patch	Location	Ground assessment		Air photograph 24/1/06		% change in area	Period (years)	% change per year
		Area (m ²)	Date	Area (m ²)	Comments			
		a		b		c	d	
A	37°50.709' 149°47.397'	466	25/11/07	516	Broad, very diffuse boundaries, sparse growth, mixed with and in part bounded by <i>Austrostipa</i>	-10	1.836	-5.4
J	37°50.700' 149°47.405'	139	6/12/07	131		+6	1.865	4
D	37°50.641' 149°47.415'	129	29/11/07	87	Patch boundaries unclear	+48	1.844	26
S	37°50.701' 149°47.562'	100	9/5/09	72		+39	3.287	12
N	37°50.733' 149°47.499'	89	18/12/07	67		+33	1.899	17
O	37°50.760' 149°47.527'	58	9/5/09	39		+49	3.287	15
F	37°50.658' 149°47.422'	54	4/12/07	49	Extent unclear	+10	1.860	5
C	37°50.686' 149°47.400'	44	29/11/07	53	Diffuse patch, boundaries unclear	-17	1.844	-9
T	37°50.753' 149°47.485'	43	9/5/09	41		+5	3.287	2
K	37°50.722' 149°47.419'	22	10/12/07	23		-4	1.877	-1
Q	37°50.676' 149°47.518'	22	9/5/09	24	Patch difficult to discern	-8	3.287	-2
G	37°50.743' 149°47.415'	21	5/12/07	21		0	1.863	0
I	37°50.673' 149°47.409'	17	6/12/07	-	Unclear	-	1.865	-
H	37°50.743' 149°47.403'	11	5/12/07	7		+60	1.863	31
M	37°50.697' 149°47.477'	9	18/12/07	8		+13	1.899	7
L	37°50.694' 149°47.470'	7	18/12/07	10		-30	1.899	-16
B	37°50.744' 149°47.390'	5	25/11/07	12	Very small patch, boundaries unclear	-58	1.836	-32
E	37°50.660' 149°47.466'	5	4/12/07	5	Very small patch, boundaries unclear	0	1.860	0
P	37°50.746' 149°47.553'	3	9/5/09	2		+50	3.287	15
R	37°50.690' 149°47.538'	1	9/5/09	1	Tiny patch, not identifiable	0	3.287	0

Laverton North Grassland, Victoria

Similar problems were encountered in interpretation of aerial photography of Laverton North Grassland as at the other grasslands. A further difficulty was the more frequent presence of more or less uniform stands of *Austrostipa bigeniculata* (Hughes) S.W.L. Jacobs & J. Everett which appeared very similar to those of *N. neesiana* in remote sensed images and, as evident on the ground, frequently co-occurred with *N. neesiana*. Indeed some *N. neesiana* patches had pronounced bands of this native grass on their edges. In general the patches at Laverton North carried much lower grass cover, with a higher content of native grasses, and a much higher proportion of bare ground, and were more diffuse than at Yarramundi Reach and Dudley Street grasslands. Several of the measured patches contained only sparse *N. neesiana*, or were highly irregular in shape, and a number contained zones where other grasses were possibly more dominant. Probably all but the smallest patches included tussocks of native grasses. These difficulties indicate that wide error margins for the areas calculated by ground measurements and air photo interpretation.

Nevertheless, the data (Table 2.10) show a very strong contrast to the situation at Yarramundi Reach and Dudley Street grasslands. Five of 18 patches at Laverton North apparently decreased in area over the periods assessed, and no change in size was recorded for three additional patches. The assessed rates of change in the areas of *N. neesiana* patches was markedly less than in the senescent grasslands, with a maximum increase of c. 30% per annum.

Major expansions of the *N. neesiana* populations at this site occurred in an earlier period and were clearly associated with degradative historical management regimes. Severe overgrazing occurred in the 1970s, soil disturbance from earth moving equipment associated with construction activity led to small-scale elimination of native vegetation in the 1980s and early 1990s, and *T. triandra* senescence probably occurred in the period when burning was not undertaken. Grader scrapes that removed all of the standing vegetation and 50-80 mm of soil were one method used in attempts to re-establish rare native plants at this site (Morgan 1999b). Some *N. neesiana* patches delineated on the ground could clearly be correlated with major disturbances shown in older photographs, including soil disturbance, the installation of an oxygen pipeline, regular mowing, and livestock tracks, although other patches could not be correlated with such damage.

Deliberate burning is believed to be the only management practice undertaken since 2002 in the area of the grassland where the assessed patches occurred. The size of some patches was estimated to have reduced under the regime of regular burning. Overall the fire-based management appears to have resulted in stabilisation of infestations and may have favoured partial recolonisation by native grasses. In terms of *N. neesiana* populations, reduction of *T.*

triandra biomass and consequent prevention of *T. triandra* senescence is probably the most important benefit of regular burning. But burning has also resulted in a very open sward structure with large inter-tussocks spaces suitable for high populations of seed-harvesting ants. These destroy a large proportion of *N. neesiana* panicle seeds, thus contributing greatly to restricting its dispersal. Fire destroys grass seed on the ground (Morgan 1999a), and a fire regime that was timed to coincide with *N. neesiana* seed production (late spring-early summer) may enable the later flowering *T. triandra* to flower and seed post-fire, if at a much reduced level, a regime that could possibly improve *N. neesiana* control and advantage the dominant grass.

The total area occupied by *N. neesiana* at this grassland has been limited by the near absence of seed-dispersing mammals (few rabbits and hares) and the flat terrain, but seed movement over a few metres by ants has been observed. *Nassella neesiana* is nevertheless present across the whole Reserve.

Discussion

Errors and accuracy

Difficulties in interpretation of remotely sensed imagery and reconciliation of image interpretations with patch areas measured on the ground mean that only general trends can be firmly established from the foregoing data. Measurement and expression of accuracy of maps derived from remotely sensed data are difficult because of the many types of potential errors, lack of agreement on appropriate error measurements and their derivation, and basic flaws in widely used approaches (Foody 2002). The probability of correct classification of an image area or pixel decreases with decreasing patch size and increasing heterogeneity in the landscape or of land cover types (Smith *et al.* 2003, Boschetti *et al.* 2004). But the probabilities of correct/incorrect classification for each individual class of land cover within a classification are not consistently affected by these variables (Smith *et al.* 2003). When remotely sensed imagery is used to assess land cover dynamics, the assessment of accuracy is even more difficult, and there is “no standard approach” (Foody 2002 p. 195). Errors of omission, in which an area that belongs to a particular class is overlooked or not registered, and errors of commission, in which an area is misclassified, are two major error sources in interpretation of remotely sensed images. Error estimation is also dependent on the often untested assumption that one data set (e.g. the ground assessment) represents truth, to which the other (the image interpretation) is compared (Foody 2002, Boschetti *et al.* 2004). At its simplest, an accuracy assessment can be made by comparing areas simultaneously measured on the ground and from the remote image, however both data sets may contain such classification errors (i.e. misidentification of the dominant grass) as well as locational errors

(e.g. patch positions incorrectly located). Error measurements that have been widely used typically ignore boundary complexities, which introduce the likelihood of further difficult-to-quantify error components, such as ‘mixed pixels’ which cannot be allocated into discontinuous classes (Foody 2002). Whatever the resolution of an image there are always ‘mixed pixels’ (Foody 2002). However the identification of bands of mixed pixels was the key element in this study because the aim was to determine changes in locations of boundaries and edges. The main error issues in this study therefore appear to be misclassification (incorrect identification of *N. neesiana* or not-*N. neesiana* areas), and smoothing or interpolation across bands of ‘mixed pixels’ in zones of heterogeneous vegetation.

No attempt has been made to quantify error in this study because of these difficulties and complexities and the highly variable range of remote image products assessed. Errors are suggested by the failure to detect in the imagery some patches recognised on the ground, and by a number of cases where there appear to be marked differences in areas of patches measured on the ground and in near-contemporaneous images. Failures to detect patches assessed on the ground in images, as at Laverton North, may be related to positional accuracy mismatches between the images and the ground and GPS measurements. But more likely this was due to the very open nature of this grassland during particular times, the diffuse nature of many *N. neesiana* patches and boundaries, and the poor quality of available images. In practical terms, contemporaneous dichotomous (*N. neesiana*/not-*N. neesiana*) interpretations of aerial imagery and ground vegetation were undertaken and found to be well correlated, but accuracy measures could not be obtained for historical images because of their widely variable quality and the impossibility of contemporaneous ground truthing.

General trends

Despite these caveats, the interpretations of aerial photos and associated studies on the ground indicate clearly that historical changes in infestation areas have been strongly influenced by the health of surrounding grassland and the differing management and disturbance regimes at the sites. *Nassella neesiana* invasions tended to be slow, except where the native grassland was in poor ecological condition (Table 2.11). The results also give broad order of magnitude estimates of *N. neesiana* expansion rates under these different regimes. The most rapid rates of expansion in patch areas occurred in the unmanaged grassland at Yarramundi Reach, where large scale senescence dieback of *T. triandra* was recently occurring, accompanied by alarmingly rapid expansion of *N. neesiana*. The Dudley Street study confirms that the boundaries of *N. neesiana* infestations moved rapidly where senescence was high and remained stable where there was no senescence. The highest linear expansion rates were measured on the roadside at Dudley Street, in a frequently mown zone (Fig. 2.6). The

Laverton North studies suggest that the ‘abundance trajectory’ (Byers *et al.* 2002) of *N. neesiana* need not necessarily always trend upwards. A patch at Crace was relatively stable under the regime of moderate to intense grazing.

Table 2.11. Selected estimates of changes in the area of *N. neesiana* infestations at four grasslands, derived from ground measurement (usually the “final date” and “final area”) and interpretation of aerial photographs (“initial date” and “initial area” and sometimes final area and date).

Site	Area	Comparison	Initial date	Final date	Initial area	Final area	Rate of change (% year)
Dudley St	central area	photos	31/3/01	21/1/05	19.6 ha	26.2 ha	+7
Dudley St	patch	photo/ground	31/3/01	14/10/07	462 m ²	674 m ²	+7
Yarramundi	patches	photo/ground	21/1/05	5/07 or 10/08	8-160 m ²	12-369 m ²	+12 to +112
Crace	patch	photos	22/12/02	31/3/08	554 m ²	599 m ²	+2
Laverton North	patches	photo/ground	24/1/06	9/5/09	24-72 m ²	22-100 m ²	-2 to +15



Figure 2.6. Mowing the road verge along the south-west edge of the Dudley Street grassland, where very rapid linear expansion rates of *N. neesiana* were measured. Mowing enhances spread by increasing native grass mortality and by dispersal of *N. neesiana* seed.

Rates of change

Rates of areal expansion measured at the Australian sites (Table 2.11) are broadly in agreement with those recorded and estimated in New Zealand (Table 2.1). Under suitable conditions, infestations can rapidly expand. Patch expansion rates of c. 1 m per year appear to be common, and increases in area of c. 10% per year at the patch and site scale occur in the absence of appropriate management.

Habitat heterogeneity has a strong influence on the rate of change of infestation dimensions. Areas of intact, healthy grassland appear to be resistant to invasion, but areas within a few metres may have much reduced resistance. The most rapid expansion rates were observed at the unmanaged, unburnt, grassland at Yarramundi Reach, where senescence of *T. triandra* was widespread and severe. However some *N. neesiana* patches in areas of that site where the *T. triandra* was healthier remained relatively stable. The trajectory from 2005-2008 was towards massive, irreparable 'collapse' of much the *T. triandra* matrix, accompanied by expansion and coalescence of discrete patches of *N. neesiana*.

Over the period from 2002 to 2008 infestations expanded rapidly in mown zones along the north verge of Dudley Street and on the north side of the Dudley Street grassland and into areas of senescent *T. triandra*. Where *N. neesiana* patches abutted healthy *T. triandra* grassland the infestation boundaries remained relatively stable over a period of several years. Mowing probably accelerated the elimination of competing *T. triandra* and resulted in more rapid transition to almost pure *N. neesiana* stands, particularly along the frequently mown road verge, due to both increased dispersal of *N. neesiana* seed by the mowing equipment and differential negative effects of repeated close cutting on the native grasses.

Effects of grazing

Livestock grazing is a degrading pressure in *T. triandra* grasslands and facilitates weed dispersal and invasion, but is preferable to the complete absence of biomass reduction management (Wong and Morgan 2007). Lunt and Morgan (2000) found that *N. neesiana* presence and density was strongly negatively correlated with that of the dominant grass (*T. triandra*) and was probably a long-term result of destruction of *T. triandra* by previous heavy grazing and ploughing at Derrimut grassland.

At Crace, a grassland managed by grazing of kangaroos and strategic grazing of cattle, the infestations remained more or less stable over the period of study. Although the presence of these grazers would presumably enhance *N. neesiana* seed dispersal, it also greatly limited *N. neesiana* seed production. *Nassella neesiana* and the dominant native grass *T. triandra* were kept very short in the studied areas over the period 2006-2008 by this grazing (see Figs. 2.4 and 2.5). The density of *N. neesiana* seed production at Crace appeared to be only a small fraction of that in the ungrazed Yarramundi Reach grassland. Perhaps the most important outcome from biomass reduction under the grazing regime at Crace was the prevention of *T. triandra* senescence. A large proportion of this grassland was examined on the ground and no senescent stands were found. However numerous small patches and isolated plants of *N. neesiana* clearly occurred in situations resulting from high intensity grazing, including around gates and along animal tracks (Fig. 2.7). The most heavily infested areas on the western side

of the Reserve appeared to have long histories of high rabbit densities or intensive human impact associated with previous military uses of the sites.

Although Laverton North Grassland Reserve has not been grazed since it was reserved in 1983, its long history of intensive utilisation by livestock appears to have predisposed much of the area to invasion. The positions of various infestations corresponded with areas denuded by grazing, in particular along stock trails.



Figure 2.7. *Nassella neesiana* patch G, Crace Grassland, ACT (outlined approximately in yellow), 21 October 2008, was crossed by a heavily trafficked Grey Kangaroo track and may have originated as a result of such devegetation.

Effects of mowing

Rapid spread and persistence of *N. neesiana* in mown zones is probably attributable to two main factors: decreased survivorship and biomass production of native grasses when frequently cut short (Chan 1980, Nie *et al.* 2009), and much enhanced *N. neesiana* seed dispersal on slashing and mowing machinery (Liebert 1996, Trengrove 1997, Erakovic *et al.* 2003, Erakovic 2005, Moerkerk 2005a 2005b 2006a 2006b). Bruce (2001) found that *N. neesiana* was generally more abundant at sites in the ACT that were mown to some extent, that it was never absent from areas that were entirely mown, and at infested sites where mowing occurred it was generally spreading from mown into unmown areas. In fact, the overall distribution of *N. neesiana* in the ACT has been viewed as extremely well correlated with mown areas (Bedggood and Moerkerk 2002).

Chan (1980) demonstrated that repeated close (2 cm above ground) mowing at intervals of ≤ 3 months of dominant native grasses *T. triandra*, *Austrostipa bigeniculata* and *Austrodanthonia* spp. resulted in reduced yields and reproductive fitness. The least affected of the native grasses examined was *Bothriochloa macra* because of its low habit and the prevalence of

prostrate tillers. Similar results were obtained by Nie *et al.* (2009) on a range of native grasses cut at 3-5 week intervals to a height of 2, 5 or 10 cm. All species tested had reduced survivorship when cut to 2 cm height, but plant survival was least with the two C₄ grasses, *T. triandra* (c. 51%) and *B. macra* (c. 57%). Cutting to 5cm increased survivorship to c. 85% with *T. triandra* and >95% with *B. macra*. Cutting at 5 and 10 cm enabled *T. triandra* to increase its shoot biomass compared to the 2 cm cut far more than the other species. These data indicate that close mowing of native grass swards will preferentially eliminate *T. triandra*. Chan (1980) also found that the timing of mowing in respect of the seasonal phenology was important. *Themeda triandra* appears to have another feature that prejudices its survival when repeatedly mown. Tussocks gradually accumulate litter and soil, so that the base of older tussocks tends to be markedly higher than the surrounding ground surface. The tendency to form mounds results in further elevation of the axillary buds, making them more susceptible to mowing. However Groves (1975) found that the seedlings of a *T. triandra* provenance from Kosciuszko National Park had wider and shorter leaves and a more prostrate form than a Canberra provenance, with new tillers arising nearly horizontally. Such a form may be better adapted to mowing and grazing.

Nassella neesiana appears to have a more prostrate tillering habit than *T. triandra* and most of the subdominant native grasses. Grech (2007 p. 4) for example considered its habit to more closely resemble that of *Lolium* spp. and *Dactylis glomerata* L. than the “very pronounced tussock growth” of *Nassella trichotoma* and *Poa labillardierei* Steud. Erakovic *et al.* (2007) observed that slashing of roadside *N. neesiana* infestations is known to “encourage the formation of dense flat ... swards as upright plants are eliminated”. The ability of *N. neesiana* to produce near-horizontal tillers when frequently mown, as noted by City of Whittlesea (no date), appears to be a trait expressed in much of the Australian *N. neesiana* population. However under regimes of frequent mowing, the possession of tillers that produce seeds (basal cleistogenes) may be as important a factor in the displacement of native grasses by *N. neesiana* as differential survivability when cut to low heights. These qualities have enabled the proliferation of *N. neesiana* in nature strips in Canberra (Jenny Cameron and Sarah Sharp pers. comms.) and have helped propel its replacement of native grasses in mown strips along pathways, such as the Yarramundi Reach bicycle path (Fig. 2.8). It is therefore worth reiterating that the whole of Yarramundi Reach was managed by mowing several times a year until 1995, when the regime was changed to mowing one third of the area each year (Frawley *et al.* 1995), and that *N. neesiana* has been present at the grassland at least since 1995 (Berry and Mulvaney 1995).



Figure 2.8. Yarramundi Reach grassland, ACT, 7 May 2007, showing the bicycle path and Black Mountain in the background. The wide mown zone along the path is almost entirely dominated by *N. neesiana*. A sharp boundary with areas dominated by *T. triandra* occurs at the edge of the mown zone in many places (e.g. far left) but some unmown areas have been partially invaded (e.g. right foreground).

Effects of fire

No general expansion of infestations occurred at Laverton North, indeed some patches appeared to have contracted under a management regime of regular (3-4 year) burning. A lack of vertebrate vectors of *N. neesiana* seeds at this grassland (few rabbits and hares and little human activity) has probably played a role in restricting further spread. Most of the studied patches at Laverton North clearly occurred on areas that were previously denuded of the dominant native grasses by earthmoving equipment, road construction or grazing. However some areas similarly damaged were reoccupied by native grasses. In contrast the absence of frequent fire at Yarramundi Reach resulted in rapid extensive invasion of *N. neesiana*, evidently due to *T. triandra* senescence dieback.

Hocking (2005b) investigated the effects of fire on *N. neesiana* under low rainfall conditions. Late spring burning was found to reduce the population densities of mature *N. neesiana* tussocks by over 90% but increase the densities of small and very immature tussocks, due to fragmentation of some large plants. Early spring burning also reduced the density of large tussocks, and burning reduced tussock area by more than 75%. Fire in late spring removed all the viable seed and approximately halved the production of new seed. Britt (2001) found that

burning of *N. neesiana* swards, after application of 1 litre of methylated spirits to square metre areas surrounded by a metal frame, eradicated adult plants in an infested pasture. The effect of burning on the size of plants is one reason why infestations were much harder to identify at Laverton North than at the ACT grasslands. Fire also results in some 'subdivision' and mortality of *T. triandra* tussocks. McDougall (1989 p. 42) found that *T. triandra* tussocks at Laverton North fragmented after burning "forming colonies rather than discrete plants", with four times more plants in burnt areas than in unburnt, but that burnt areas carried more seedlings. Henderson (1999) found that there appeared to be some death of *T. triandra* tussocks at Laverton North Grassland when burnt once or twice in two years under drought conditions, but death of tussocks was neither widespread nor uniform in the areas burnt. Differential negative effects of fire on *N. neesiana* compared to the possibly better adapted native species may partly explain the much higher diffuseness of *N. neesiana* patches at Laverton North.

It can be inferred from the work of Peart (1979 1984) that *N. neesiana* panicle seed is adapted for surface germination and has little capability of self burial. *Nassella neesiana* has a persistent, very robust, twice-bent awn (Barkworth 1990, Edgar *et al.* 1991) which probably impairs more than very shallow seed burial. Bourdôt and Hurrell (1992) found that 99% of the soil seed bank in a New Zealand pasture was in the top 25 mm of the soil. The soil seed bank of panicle seed is primarily in surface litter, or at the soil surface, where it is subject to destruction by fire. Seeds of *T. triandra* by contrast appear to be able to achieve shallow burial (Peart 1979), possibly assisted by the readiness with which the awns are shed (Groves and Whalley 2002). African studies by Lock and Milburn (1970) indicate that the seeds bury themselves at a mean depth of 11 mm, where they are protected from fire, or amongst the base of the plant, and more seedlings occur within established plants than in intertussock spaces.

The *T. triandra* seed bank thus appears to have pronounced fire survivability and fire enables improved establishment. But the production of basal cleistogenes, as possessed by *N. neesiana*, is reportedly important in maintaining a species under conditions of frequent fire (Dyksterhuis 1945) and in *N. neesiana* the basal cleistogenes in particular are likely to survive fire in situ (Bourdôt 1989). Under a regime of regular burning it may be that neither species has a pronounced advantage in regards to seedling recruitment, although this may be dependent on the precise timing of the fires. Fire evidently causes occasional mortality of both *T. triandra* and *N. neesiana* and a regime of frequent fire may explain the diffuse nature of the infestations at Laverton North. *Nassella neesiana* may be more likely to maintain occupancy via cleistogenes where fire kills one of its tussocks, but may be less likely to occupy the site of a killed *T. triandra* tussock because of reduced production of panicle seed

and a soil seed bank that is more concentrated close to the surface. Reliance solely on panicle seed with better burial capabilities may advantage *T. triandra* in colonising areas where *N. neesiana* tussocks have been killed. Theory predicts that high perimeter to area ratios increase vulnerability to invasion (Byers *et al.* 2002). Further data analysis is required to determine whether an apparent greater admixture of *T. triandra* in high perimeter: area *N. neesiana* patches at Laverton North is in fact evident and thus suggestive of *T. triandra* reinvasion of areas it formerly occupied.

Management and restoration

A number of the grasslands heavily invaded by *N. neesiana* may be characterised as ‘enriched grassland’ as defined in the state-and-transition model of McIntyre and Lavorel (2007). Such areas have been cultivated or managed for grazing, remain nutrient enriched as a result of such disturbance, and tend to be dominated by robust exotic perennial grasses and exotic rosette-forming herbs such as *Plantago lanceolata* L. and *Hypochoeris radicata* L. Many former pastures on the edges of urban areas are in this state (McIntyre and Lavorel 2007) and some disused pastures dominated by *Nassella* spp. can be included in this category. In the presence of intense propagule pressure from exotic grasses, major *T. triandra* senescence dieback enables direct transition from the ‘reference grassland’ state to the ‘enriched’ state (Wijesuriya 1999, Wijesuriya and Hocking 1999). Enriched grassland areas have various similarities with the “old fields” or “ex-arable fields” targeted for grassland restoration in Europe and North America, including residual soil fertility and dispersal limitations on native species recolonisation, that provide severe constraints on natural regeneration of the community (Öster *et al.* 2009). Times scales well in excess of 50 years can be expected for natural reassembly to a state approximating a semi-natural grassland in these northern hemisphere areas (Öster *et al.* 2009). Changes to a degraded state may be thought of as irreversible or very hard to reverse transitions across ecological thresholds “triggered by events that are typically unprecedented” and which result in a plant community “constrained by a different set of biological and soil processes” (Sadler *et al.* 2010 p. 434). More readily reversible transitions can be used to define ‘phases’ within a state (Sadler *et al.* 2010): the gradual densification of a *T. triandra* sward could be so classified, with fire the process that reverts the system to the initial phase, and an ultimate phase of high density which is perhaps twice as long as the minimum fire return interval and is determined by local edaphic and climatic conditions.

Conclusions

Possibly the most important finding from this component of the study is an obvious one: *N. neesiana* infestations are not transient phenomena but occupy the ground more or less

indefinitely in the absence of powerful intervention, and constitute an alternative stable state. The second major conclusion is that the expansion rate of *N. neesiana* infestations is rapid when management activity is inappropriate. When *T. triandra* is allowed to senesce through lack of biomass reduction, resistance to invasion collapses and linear expansion rates of >5 m per year can be expected. Mowing/slashing regimes that involve frequent short cutting result in rapid expansion along roadsides, in some instances that were measured rates of spread were even faster than in some areas of severe senescence dieback. Differential mortality of native grasses and *N. neesiana* when closely and frequently cut may be a more important driver of invasion in such mown areas than dispersal of propagules by mowing machinery alone. Where infestations abut areas of native grassland in good condition their boundaries are stable over periods of several years. Grazing regimes may result in the stabilisation of infestation boundaries, at best, but at worst appear to promote invasion by killing *T. triandra* and through the creation of bare ground in intensively trafficked areas. A management regime consisting solely of regular fire appears to result in lower expansion rates or the containment of infestations, and may gradually reduce population density and areal coverage of patches. In the longer term native grasslands kept healthy by biomass reduction are resistant to *N. neesiana* invasion, and associated losses of plant biodiversity are kept low.

Although the findings of this study appear robust, the measured trends reported should be characterised as preliminary ‘rough and ready’ approximations: a very limited set of suitable images were qualitatively assessed, with little constraint on the possibility of observer bias. Infestation boundaries are not smooth, and invasions fronts must always first consist of small, sometimes scattered individuals that cannot be identified from the types of images used and may be difficult to detect on the ground. Further studies should employ established GIS systems, geodetic techniques that correct for projection errors and a range of defined image metrics including textural, pixel-based measurements and structural (patch area/perimeter) measures to assess time series images, to better quantify system trajectories (Sadler *et al.* 2010). Meaningful error estimates should be incorporated (see Foody 2002, Smith *et al.* 2003, Boschetti *et al.* 2004). The increasing quality and availability of remotely-sensed imagery with much shorter periods between images, due to better satellite coverage, should make the task considerably easier in the future. Assessment of the biodiversity impact of *N. neesiana*, at least by determination of rates of displacement of *T. triandra* grassland, appears to be eminently feasible on an ongoing basis, and such a system could be deployed to trigger management intervention before ‘irreversible’ transition of *T. triandra* grassland to a degraded state.