Pinus radiata invasion in New South Wales: the extent of spread

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Summary

Recognition of invasive species in the early stages of invasion is a major priority for weed research and yet too often invaders only receive adequate attention when they are already widespread and control is costly. Many species of the *Pinus* genus are successful invaders imposing harmful ecological impacts across the southern hemisphere. In Australia, the potential for pine invasion is high because more than one million hectares of commercial pine plantations are cultivated, which often border native vegetation. To date, quantitative assessments of the extent of invasion have been limited to small geographic areas. We surveyed the vegetation surrounding all the major *Pinus radiata* plantations in NSW in order to determine the current extent of invasion and to help prioritize the species as an invader. Nine out of 29 sites bordering plantations were heavily invaded; suggesting that on a landscape scale the species is yet to have a large impact. However, at the most infested sites pine basal areas reached more than 50 m^2 ha^{-1} and pines were found up to 10 km from the source plantation. The World Heritage Blue Mountains region has experienced some of the highest levels of invasion, thereby demanding adequate control measures to protect areas of high conservation value. Given the large potential for spread and known impacts of invasive pines elsewhere, effective control in the early stages of invasion and the implementation of measures to prevent further spread of the species are paramount.

Keywords: eucalypt woodland, weed, mapping, impact.

Introduction

National attention for alien plants is necessarily focused on Australia's Weeds of National Significance (Thorpe and Lynch 2000), as they are perceived to pose a high risk to biodiversity. However, recognition of high impact weeds in the initial stages of invasion is necessary in order to enable early action and prevent them from becoming future weeds of national importance. This recognition requires identification of the point when naturalized species enter a higher risk and impact category. Two major components of the impact of an invading species are the range, i.e. the areal extent of the species, and the abundance, i.e. the typical density of the invader (Parker *et al.* 1999). Direct knowledge of both these components can help prioritize invaders yet to receive attention.

Species of the genus *Pinus* have enjoyed major success as invaders across the Southern Hemisphere (Richardson *et al.* 1994). They impose severe impacts on natural systems from reductions in species richness (Richardson and Van Wilgen 1986) to changes to ecological processes such as water flow (Van Wyk 1987), fire intensity and soil erosion (Scott and Van Wyk 1990). Australia cultivates almost one million hectares of pine plantations, with the majority composed of *Pinus radiata* (Wood *et al.* 2001). Dispersal of winged pine seed via wind and partial cones containing seeds by birds has resulted in the establishment of self-sown pine (wildling) populations in a range of vegetation types, predominantly eucalypt vegetation (Williams and Wardle 2007a). Despite knowledge of pine spread in most Australian states and calls for an assessment of the specific impacts of pines in eucalypt vegetation (Williams and Wardle 2007a), quantitative data on the extent of spread are limited to site-specific studies (Burdon and Chilvers 1977, Dawson *et al.* 1979, Williams and Wardle 2005).

The threat posed by pine invasions to ecosystems elsewhere and the common lag time associated with the establishment of woody species (Kowarik 1995, Wangen and Webster 2006) suggests that *P. radiata* has the potential to have a large impact in Australia. This study aimed to quantify and map the extent of invasion of *Pinus radiata* in NSW. Knowledge of the area invaded and the spatial distribution of infestations will help prioritize the species as an invader and target control operations. Information on reproductive status obtained by counting female cones from the ground on each wildling tree was obtained in order to determine the potential for further spread directly from these self-sown wildling trees.

Methods

Study area

The study area encompassed 29 *P. radiata* plantation sites in NSW (Figure 1) across four forestry regions: Macquarie, Hume, Northern and Monaro. The largest distance between two sites was 693 km, between Riamukka State Forest in northern NSW and Bondi State Forest, near the southern border. The two closest sites were Wingello A and Wingello B; 3.2 km apart. The Monaro region was composed of six sites that are geographically disjunct. Four sites, Penrose, Belangelo, Wingello A and Wingello B occur in the Moss Vale region located approximately 140 km south west of Sydney. The remaining two sites in the

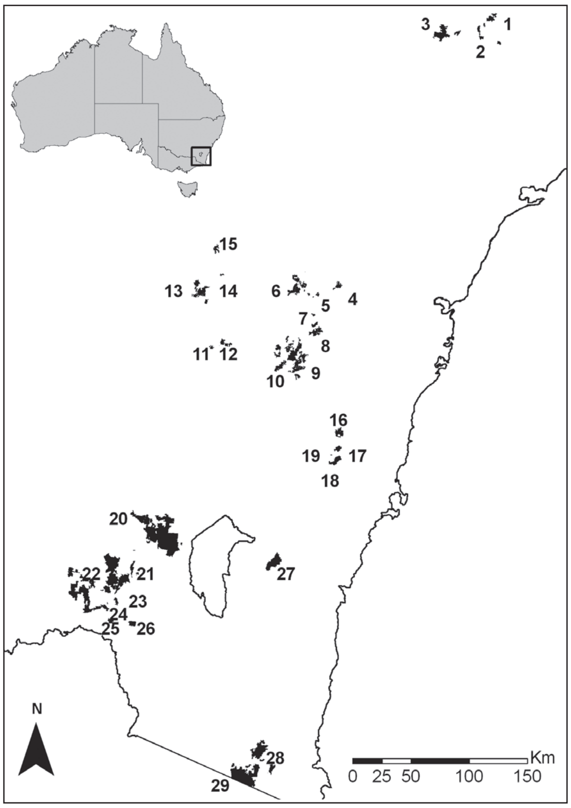

Figure 1. Twenty-nine plantation sites surveyed for *Pinus radiata* invasion in NSW. 1. Riamukka 2. Nowendoc 3. Hanging Rock 4. Newnes 5. Lidsdale 6. Sunny Corner 7. Hampton 8. Jenolan 9. Gurnang 10. Vulcan 11. Pennsylvania 12. Roseberg 13. Mount Canobolas 14. Kinross 15. Mullions Range 16. Belangelo 17. Penrose 18. Wingello A 19. Wingello B 20. Buccleugh 21. Blowering Dam 22. Green Hills 23. Bago 24. Mannus 25. Bogandyera 26. Clarkes Hill 27. Tallaganda 28. Coolangubra 29. Bondi.

Table 1. Climate and plantation attributes of the 29 plantations surveyed in NSW.

Plantation	Plantation size (ha)	Residence time (years)	Mean annual rainfall (mm)	Altitude (m)	Border surveyed (km)	% of total border surveyed
MACQUARIE REGION						
Gurnang	11 924	74	995	1 150	34.7	22.5
Hampton	1 367	39	946	1 150	3.7	16.9
Jenolan	3 929	77	967	1 200	29.1	51.2
Kinross	467	20	870	1 000	1.9	14.2
Lidsdale	751	83	761	950	7.5	58.1
Mount Canobolas	9 133	70	1 079	1 000	16.6	11.9
Mullions Range	2 057	83	964	900	16.7	44.0
Newnes	2 171	93	1 072	1 100	38.7	86
Pennsylvania	2 695	36	851	700	37.3	81.3
Roseberg	787	17	847	800	18.4	100
Sunny Corner	9 866	83	939	1 100	27.3	20
Vulcan	18 556	78	861	1 200	7.9	3.4
HUME REGION						
Bago	8 537	84	1 399	700	24.5	36.4
Blowering Dam	2 849	64	989	700	10.2	23.6
Bogandyera	1 402	10	740	650	5.1	19.1
Buccleugh	41 627	78	1 300	800	44.2	16.4
Clarkes Hill	1 681	22	740	900	2.9	15.1
Green Hills	11 035	85	1 399	700	7.5	12.2
Mannus	372	70	982	550	8.0	67.8
Tallaganda*	1 732	37	748	1 100	16.4	55.4
NORTHERN REGION						
Hanging Rock	7 720	83	1 414	1 100	45.3	53.8
Nowendoc	2 830	22	1 038	1 200	27.2	76.6
Riamukka	3 351	33	1 114	1 300	14.3	51.6
MONARO REGION						
Belangelo	1 052	87	876	650	8.6	47.8
Bondi	21 116	77	970	900	67.2	47.2
Coolangubbra	8 963	35	646	580	39.5	23.5
Penrose	1 405	74	1 017	700	23.8	70
Wingello A	1 383	80	1 093	650	51.1	85.0
Wingello B	109	40	707	650	4.3	91.5

Note: Tallaganda is officially considered to be part of the Monaro forestry region, although it has been included in the Hume region in this study as it is in closer geographic proximity to other sites within the region and a single vegetation database for the Hume region sites also covered Tallaganda.

region, Bondi and Coolangubra are located a further 250 km south near the Victorian border. Site attributes of the plantations are shown in Table 1. The size of the plantations ranged from 109 ha at Wingello B to more than 41 000 ha at Buccleugh. The age or residence time of the plantations spanned several decades from 10 years at Bogandyera to 93 years at Newnes (Table 1). It is important to note that the portion of the border surveyed is not consistent across sites.

Survey techniques

At each site, the level of invasion was quantified by driving the border of the plantation and scoring the level of pine infestation in the adjacent vegetation. Scoring involved allocating an 'infestation index' for each 100 m interval and calculating a mean infestation index per 100 m for each site. Each 100 m interval is referred to as a 'sample'. Scores ranged from 0, indicating no pines present to 5, which represents mature pines overtopping the eucalypt canopy. The index was designed to have simple, clearly defined categories and be quick to implement. The scoring framework required features that would enhance the number of comparisons of the level of invasion between sites and facilitate future comparisons by land managers over longer time scales. Divisions were based on a combination of pine basal area and density (Table 2). The index reflects both the length of time the invasion has been occurring, i.e. older large trees represent an early invasion, and the density of the invasion which is an indicator of the susceptibility of the vegetation to invasion. In order to distinguish between recent and early invasions, areas with pines greater than 10 m tall at any density were given a score of 3 or above independent of pine density. The maximum index and proportion of border with an index greater than or equal to 3 were also calculated. In areas where it was obvious that physical removal of wildlings had taken place the score was estimated using the presence of remaining pine stumps.

Table 2. Infestation index for *Pinus radiata* invasion. Every 100 m interval of vegetation surveyed along plantation perimeters was assigned an infestation index.

Infestation index	Level of infestation	Description	Pine basal area $m^2\ ha^{-1}$	Maximum height (m)
0	None	No pines present	0	0
1	Very low	Very few pines or few small pines	0–1	<5
2	Low	Small pines at density higher than level 1	1–2	<10
3	Medium	Pines at least 10 m tall at any density	2–5	>10
4	High	Tall pines at high pine density, typically at same density as native eucalypts	5–10	>15
5	Very high	Very high pine density and basal area, i.e. lots of old trees. Greater density than native eucalypts	>10	>15

The index represents the level of invasion within the first 50 m of vegetation from the plantation. Therefore each sample refers to an area of native vegetation 50 × 100 m in size. As expected, areas with high levels of infestation close to the plantation were also observed to have pines growing the furthest away from the plantation and thus the greatest area of land infested. This pattern was quantified by surveying transects placed perpendicular to the plantation in areas of high pine density. The height, diameter at breast height (dbh) and number of cones of pine trees were recorded within 20 m wide transects. Transects ended when pines were no longer present or terrain prevented further survey by foot. To help assess the time scale for any invasion, the presence of recent recruitment in the form of seedlings (pines with whorls absent) and saplings (<2 m tall) was recorded in each transect and sample. Evidence of control measures was recorded for each sample.

Difficult terrain, road obstructions and time restrictions meant that not all borders of all plantations were surveyed. Priority was given to areas where native vegetation bordered the plantation. Many of the larger plantations had substantial proportions of their boundaries abutting cleared or heavily grazed land. Field observations indicate that pines very rarely establish in these areas and therefore survey effort was focused on native vegetation.

Infestation index data are displayed using boxplots. The bottom and top horizontal lines for each category indicate the lowest and highest scores respectively. The box shows the middle 50% of scores (interquartile range). The dark horizontal line within the box indicates the median score. Circles represent outliers. The area of land invaded at each site was estimated using a combination of transect data, field observations and infestation index data. For example, where transect data provided the distance of the furthest pine from the plantation this information was extrapolated to estimate the extent of invasion for this border of the plantation. In other instances, opportunistic observations while surveying allowed an estimate of the extent of invasion on certain borders. Polygons of invaded areas were plotted onto plantation maps and the total area invaded was calculated in hectares for each plantation using ArcMap 9.1 (ESRI 2005).

Results

Of the 29 plantations surveyed, 20 exhibit low levels of invasion with a mean infestation index less than 1 (Table 3). The maximum height of pine wildlings was observed at Lidsdale (30 m) and the maximum diameter observed was 95 cm at Mannus. However, most of these sites had at least a few large wildlings present with diameters reaching 70 cm. At the two most heavily invaded sites, Mannus and Lidsdale, more than 90% of the plantation borders were heavily invaded. At the majority of sites, wildlings were restricted to within the first 200 m from the plantation and high levels of infestation (index ≥3) were restricted to less than 10% of the plantation boundary.

There were several cases of pines being dispersed long distances of 2 km or more at Mannus, Lidsdale, Mullions Range and Newnes (Table 3). The longest recorded distance was 10 km, presumably from the Mannus plantation. This information was provided by an aerial survey undertaken by the NSW Department of Environment and Climate Change. A map of NSW indicating the level of infestation for the 29 sites is presented in Figure 2. Evidence of pine control was observed at Lidsdale, Penrose, Gurnang and Canobolas.

The estimated area of land invaded by *P. radiata* and the density of invasion varied greatly between the nine most heavily invaded sites (Table 4). Lidsdale was one of the most heavily infested sites with an estimated 1800 hectares invaded. The site also experienced the highest density of invasion with pine basal areas of more than 50 m^2 ha^{-1} recorded in areas adjacent to the plantation (Williams and Wardle 2005). In general, areas with a smaller areal extent of invasion experienced lower maximum densities. Pine basal area also varied with distance from the plantation. At two sites, Jenolan and Mullions Range, peak basal area occurred at 200 m and 300 m from the plantation respectively (Figure 3). These peaks corresponded to mature pines overtopping the eucalypt canopy (Figure 4). At Mullions Range, the peak in basal area is dominated by a single pine with a

Table 3. Mean and maximum infestation index and distance of the furthest surveyed pine from the 29 plantations. Sites are placed in order of descending level of invasion.

Site	Mean (max) infestation index	% surveyed border length with index ≥3	Max height (m)	Max diameter (cm)	Furthest surveyed pine (m)
Mannus	4.64 (5)	93.8	20	45	10 000[A]
Lidsdale	4.28 (5)	90.7	30	64	2 000
Penrose	3.25 (5)	74.4	18	40	200
Belangelo	2.99 (5)	62.8	18	50	230
Wingello B	2.49 (5)	46.5	20	50	100
Mullions Range	2.41 (5)	43.7	25	95	2 200
Jenolan	1.67 (5)	28.2	30	80	400
Newnes	1.47 (5)	28.9	23	46	4 000
Wingello	1.06 (5)	16.6	20	50	80
Gurnang	0.92 (5)	11.3	15	50	700
Vulcan	0.89 (3)	2.5	15	60	50
Coolangubbra	0.60 (5)	8.9	18	40	180
Green Hills	0.60 (3)	0.1	8	10	50
Mount Canobolas	0.58 (3)	7.8	10	30	50
Blowering dam	0.58 (4)	13.7	10	20	20
Bondi	0.52 (5)	4.8	20	50	50
Sunny Corner	0.47 (3)	1.8	20	70	200
Tallaganda	0.32 (4)	4.3	11	30	200
Bago	0.3 (4)	0.1	20	70	100
Buccleugh	0.22 (5)	5.6	20	80	500
Hampton	0.22 (2)	0	10	20	20
Hanging Rock	0.07 (1)	0.4	25	50	60
Pennsylvania	0.05 (1)	0	15	30	20
Riamukka	0.04 (1)	0	10	25	20
Nowendoc	0.03 (1)	0	5	3	20
Roseberg	0.01 (1)	0	3	5	20
Bogandyera	0 (0)	0			
Kinross	0 (0)	0			
Clarkes Hill	0 (0)	0			

[A] Pines mapped from the air.

diameter of 95 cm and more than 100 cones present. One hundred and forty nine pine seedlings were found within a 20 m radius of the pine.

Percentage of reproductive pines
The percentage of wildling trees recorded as reproductive (indicated by the presence of female cones) varied across the nine most heavily invaded sites from approximately 15% at Jenolan to more than 85% at Newnes (Table 5). The mean number of cones per tree was generally low (<10) at the majority of sites but was particularly high at Newnes (mean = 34.5±6.9). There was a significant positive correlation between the number of cones on a tree and the proportion of reproductive wildlings at a site ($r = 0.86$; $P = 0.03$).

Extent of invasion within regions
There was a high level of variation in the level of invasion across regions. The Macquarie and Monaro regions were the two most heavily invaded (Figure 5). Only one site in the Hume region experienced high levels of invasion and almost no invasion has occurred in the Northern region (Figure 5). A detailed description of the variation between plantations within each region is provided below.

Macquarie Region
Four sites in the Macquarie region exhibited high levels of invasion (interquartile ranges of 3 or more) and four sites had moderate to low levels of invasion with the majority of samples falling below 1 (Figure 5). Plantations that appear relatively free of invasion include Hampton, Pennsylvania, Roseberg and Kinross. Lidsdale was the most heavily invaded site exhibiting a mean infestation index of 4.3 and the majority of samples lying between 4 and 5. The majority of invasion has occurred in a south-easterly direction towards Mount Walker on crown and state forest land (Appendix 1). Prior to the field survey, the area of infestation was estimated as 300 hectares (personal communication D. Noble), although our results indicate approximately 1800 hectares of land are invaded. In 2003, some areas of the site were surveyed in more detail for pine wildlings. Pine densities were high in areas close to the plantation (>2000 ha^{-1}) and large 20 m tall pines persisted at low densities of approximately four individuals per hectare for an estimated distance of 2 km from the plantation (Williams and Wardle 2005).

High pine densities of more than 2000 per hectare have been recorded in areas adjacent to the plantation at Newnes (Williams and Wardle 2005). Currently, the invasion is confined to the lower south-eastern edge where pines are growing at a density of 500 individuals per hectare, 450 m from the plantation. The majority of the infestation lies within State Forests land, however; Newnes State Forest is bounded by Wollemi National Park to the north and Blue Mountains National Park to the east and further expansion of the wildling population will result in an encroachment of these areas (Appendix 2).

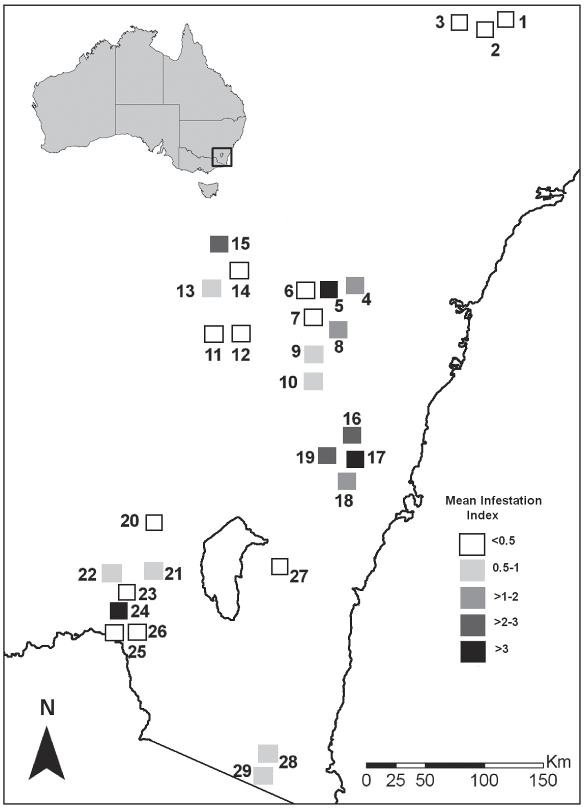

Figure 2. Twenty nine-plantation sites coded by mean infestation index.
1. Riamukka 2. Nowendoc 3. Hanging Rock 4. Newnes 5. Lidsdale 6. Sunny Corner 7. Hampton 8. Jenolan 9. Gurnang 10. Vulcan 11. Pennsylvania 12. Roseberg 13. Mount Canobolas 14. Kinross 15. Mullions Range 16. Belangelo 17. Penrose 18. Wingello A 19. Wingello B 20. Buccleugh 21. Blowering Dam 22. Green Hills 23. Bago 24. Mannus 25. Bogandyera 26. Clarkes Hill 27. Tallaganda 28. Coolangubra 29. Bondi.

Table 4. Summary of the density and aerial extent of invasion in hectares (ha) at the nine most heavily invaded sites. Land Tenure: SF = State Forest, NP = National Park, SRA – State Recreation Area.

Plantation	Maximum density (ha^{-1})	Maximum basal area (m^2 ha^{-1})	Area of land invaded (ha)	Tenure of invaded land	Appendix
Lidsdale[A]	2 425	56.1	1 800 ha	Crown land, SF	1
Newnes[A]	2 825	38.5	400 ha	SF	2
Jenolan	1 400	34.5	200 ha	SF, NP	3
Mullions Range	3 375	18.2	1 020 ha	SF, SRA	4
Mannus	900	23.4	290 ha	SF	5
Penrose	825	13.8	170 ha	SF	6
Belangelo	1 450	9.4	120 ha	SF	7
Wingello B	1 550	15.3	25 ha	Crown land	8
Wingello A	1 050	24.8	60 ha	SF	9

[A] Data for Newnes and Lidsdale were collected during a separate study (Williams and Wardle 2005).

Table 5. Percentage of reproductive pine wildlings at the nine most heavily invaded sites. Data were collected from transects placed perpendicular to the plantation boundary.

Plantation	% reproductive wildlings >5 m	Mean no. cones per tree (SE)	Number of pines surveyed >5 m
Mannus	15.8	3.5 (0.7)	260
Lidsdale[A]	48.1	7.0 (1.4)	212
Penrose	25.2	2.2 (0.3)	151
Belangelo	29.5	3.4 (1.5)	88
Wingello B	31.7	9.1 (5.1)	60
Mullions Range	57.1	12.4 (1.3)	70
Jenolan	15.6	3.6 (0.6)	83
Newnes[A]	85.4	34.5 (6.9)	96
Wingello	54.3	6.7 (1.7)	35

[A] Data for Newnes and Lidsdale were collected during a separate study (Williams and Wardle 2005).

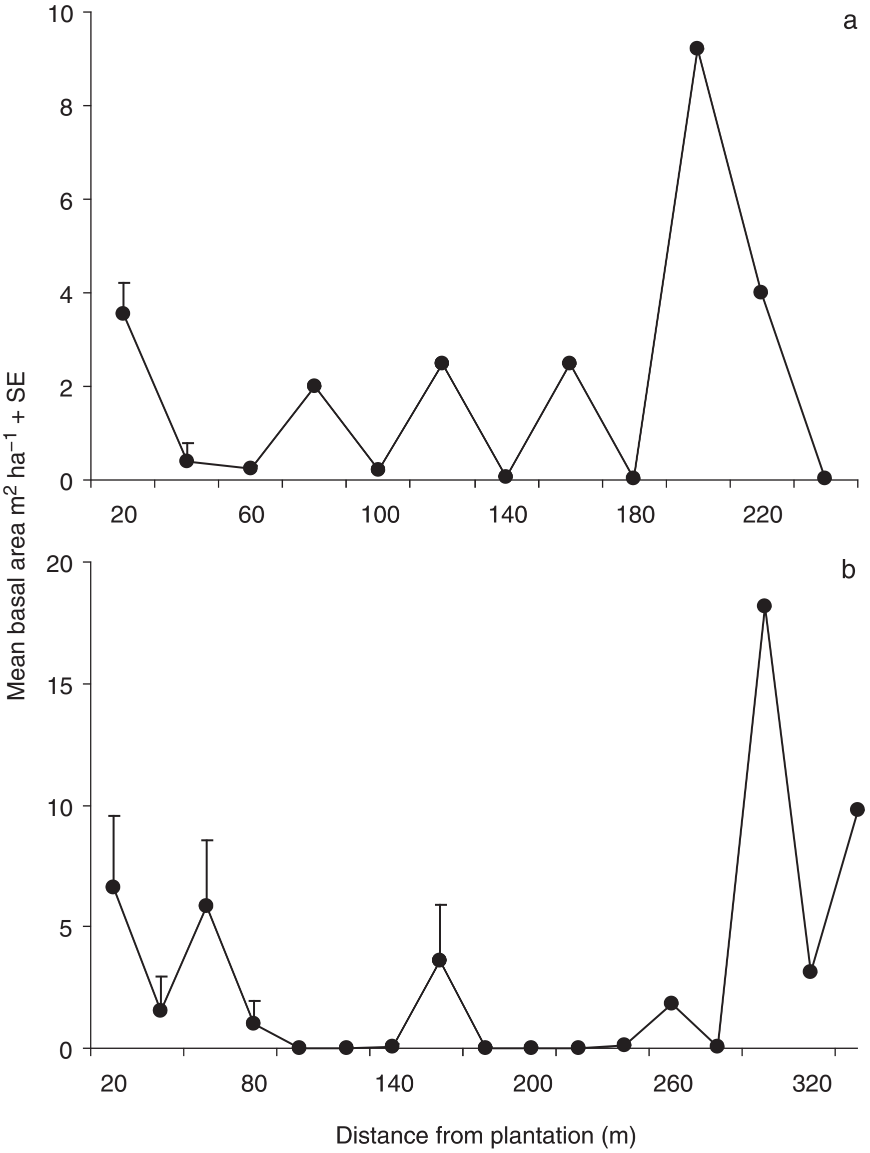

Figure 3. *Pinus radiata* basal area (m^2 ha^{-1}) with increasing distance from the plantation at Jenolan (a) and Mullions Range State Forests (b). Values are mean basal area calculated from replicate transects placed perpendicular to the plantation boundary.

Invasion levels at Jenolan State Forest were highest to the south of the plantation where pine densities were 1400 per hectare (Appendix 3). Jenolan State Forest is located in close proximity to world heritage listed vegetation in Kanangra-Boyd National Park and wildlings are currently approaching the park boundary.

Mullions Range State Forest is another of the most heavily invaded sites (Appendix 4). Large pines overtop the native eucalypt canopy at an estimated density of approximately 20 per hectare for a distance of up to 2 km from the plantation. The majority of spread has occurred on State Forest land to the east of the plantation.

The large plantation at Gurnang State Forest is directly bordered by Kanangra-Boyd and Blue Mountains National Parks. *Pinus radiata* is known to have invaded an area of approximately 50 hectares of Eucalypt woodland in the southern section of Blue Mountains National Park, adjacent to the Gurnang plantation (personal communication J. Bros). This survey recorded pine densities of up to 500 per hectare with many large reproductive pines present and a total invaded area of 300 hectares. Considerable invasion of native vegetation to the south east of the plantation has also occurred. Low levels of invasion have taken place at Sunny Corner State Forest, which is bordered by Winburndale Nature Reserve and Mount Canobolas State Conservation Area. Pines are mostly limited to within 200 m from the plantation at both sites.

Hume Region

Very little invasion has occurred within the Hume region (Figure 5). The only heavily invaded site was Mannus State Forest where large mature pines overtop eucalypt canopy at an estimated density of 100 per hectare for up to 300 m from the plantation (Appendix 5). Several *Pinus* species have also spread up to 200 m from the Pilot Hill Arboretum at Bago. Plantations that remain relatively free of invasion include Buccleugh, Blowering Dam, Bogandyera and Clarkes Hill. At Tallaganda, a small amount of invasion has occurred to the south east of the plantation where pines have spread up to 120 m into the native vegetation.

Northern Region

Very little invasion has occurred at the three northern sites; Hanging Rock, Riamukka and Nowendoc with a median infestation index of 0 (Figure 5).

Monaro Region

Plantations situated in the northern section of the Monaro region were among the most heavily invaded with significant wildling populations occurring at all four sites (Figure 5). At Penrose, large pines are invading swampland surrounding the plantation, at a density of approximately 160 per hectare (Appendix 6). More than 90% of the border is invaded and a fifth of this is at the highest level; 5. Belangelo and Wingello B are also heavily invaded, although wildlings are restricted to within 230 m and 100 m from the respective plantations (Appendices 7 and 8). Pine spread at Wingello A has primarily taken place in the northern section of the site and is limited to 80 m from the plantation boundary (Appendix 8). The two most southern plantations, Bondi State Forest and Coolangubra State Forest recorded mean infestation indices less than one. However, the sites are not entirely invasion free with some invasion occurring. At Coolangubra, pines have spread up to 180 m into the adjacent Coolumbooka Nature Reserve. At Bondi small clusters of pines have established in recently disturbed roadsides, e.g. next to soil dumps.

Discussion

Extent of invasion

Key knowledge gaps for *Pinus radiata* as an invasive species in New South Wales have been addressed in this study. Firstly, the pattern of invasion at a landscape scale was established, providing an estimate of the total area of land invaded and illustrating the variation in invasion success between sites. The results of this survey have provided a snapshot of the current level of pine invasion across NSW. As time passes, further invasion is likely and the maps of invaded areas annotated with the infestation level are an important reference point for monitoring the progress of this weed. Documenting the spatial extent of spread is the first step towards

Figure 4. Mature *Pinus radiata* overtopping native eucalypt canopy at Mullions Range State Forest. Distant pines are marked with arrows.

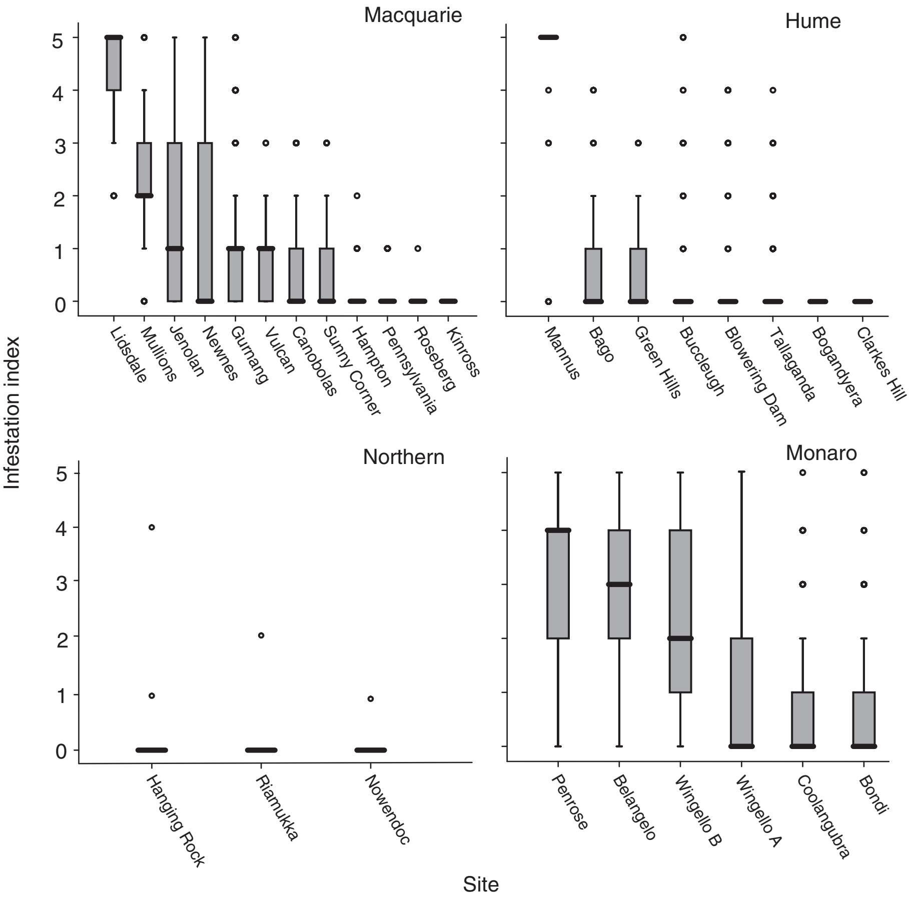

Figure 5. Level of invasion at sites within the four forestry regions. Boxes show the middle 50% of scores (interquartile range). The dark horizontal line within the box indicates the median score. Circles represent outliers. Sites are ranked in order of decreasing level of invasion. For definition of the levels of infestation index see text. Monaro region has a large latitudinal spread. The first four plantations are towards the north in the Moss Vale area of NSW and Bondi and Coolangubra are located near the southern border with Victoria.

quantifying the impacts of invasion and allows comparisons of invasion success between species and between continents (Parker *et al.* 1999). This is of particular relevance for *P. radiata*, a species that has been planted widely with varying invasion success between regions and habitat types across the Southern Hemisphere (Richardson *et al.* 1994). Within-site distribution patterns also have consequences for calculating the total area of impact. Pine densities were highly variable around the border of the plantation and with increasing distance away from the plantation. A distinction between heavy and light infestations is crucial to identify and prioritize sites for management as costs of control are heavily dependent on wildling densities (DOC 2001).

The field survey identified several significant wildling populations and a total estimated area of land invaded of almost 4500 hectares in NSW. The extent of spread is much less than observed in South Africa (34 000 ha; Richardson *et al.* 1994) and in New Zealand. Of the 150 000 hectares of land affected by conifer spread in New Zealand, two thirds is composed of *P. contorta* with *P. radiata* accounting for a much smaller area (Ledgard 2001). Our result for NSW is likely to represent only one component of the total area invaded in Australia as invasion has also occurred in the ACT (Chilvers and Burdon 1983), Victoria (Minko and Aeberli 1986) and South Australia (Virtue and Melland 2003). Additional spread is known to have taken place at sites within NSW that were not surveyed during this study. For example the total area invaded within Kosciusko National Park has been estimated at 15 000 ha (personal communication M. Pettitt), however this figure is likely to be taking into account the total area covered by widely dispersed individuals. Pines have also regenerated in eucalypt remnants adjacent to Buccleugh State Forest (Lindenmayer and McCarthy 2001), which were not a focus of this study. Additional spread of other pine species such as *P. elliotti* has occurred on the NSW north coast (personal communication M. Smith). Pines growing in windbreaks and established in urban settings are also a source of invaders particularly in the Blue Mountains region of NSW (Williams 2003).

The most heavily invaded sites are located in the central west of the state and the Moss Vale region. Wildling populations at Lidsdale and Mullions Range accounted for almost half of the total area of land invaded. The majority of the remaining sites exhibit low levels of invasion, thereby suggesting that at the landscape scale *P. radiata* has yet to reach the maximum level of impact. However, the presence of large wildling populations at sites such as Lidsdale and Mullions Range suggests that if conditions are conducive to invasion, *P. radiata* can become an established invader with a dominant presence in the community.

At many of the sites pines are invading or approaching land of high conservation value. The plantation at Penrose is bordered by swampland, which has been invaded by pines. The Temperate Highland Peat Swamps are listed as an endangered ecological community under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Evidence for pines out-competing eucalypts (Chilvers and Burdon 1983) following invasion indicates that they could be a major threat to species such as *Eucalyptus aquatica* which only grows in the catchment between Wingello and Penrose (Fairley 2004) and is listed as vulnerable under the *Threatened Species Conservation Act 1995* (TSC Act). At Sunny Corner State Forest, pines are invading habitat of the Bathurst copper butterfly (*Paralucia spinifera*), a species that is listed nationally as vulnerable under the EPBC Act. Pine wildlings have been removed from areas of Sunny Corner SF as part of a recovery program for the butterfly (NPWS 2001).

The Blue Mountains region lies within the Macquarie forestry region and contains just over one million hectares of world heritage listed vegetation dominated by temperate eucalypt forest that is protected within a system of eight National Parks. The field survey identified a number of areas within the National Park estate that are currently under threat from pine invasion. Pines are approaching the Kananga-Boyd National Park boundary and Jenolan Karst Reserve at Jenolan State Forest. Further spread from the plantation at Newnes will result in invasion of Blue Mountains National Park to the east and Wollemi National Park to the north. Isolated pines have already been recorded within Wollemi National Park boundaries (personal observations M. Williams). The eastern border of Blue Mountains National Park is being invaded by pines from Gurnang State Forest. Several other infestation sites have been documented in the region including within Abercrombie National Park (personal communication C. Banffy 2003).

Wildling recruitment

At the majority of sites, more than one third of wildlings over 5 m in height were reproductive suggesting a high potential for further invasion in these areas. Peaks in pine density and basal area at distances of up to 300 m from the plantation at Mullions Range and Jenolan are due to clusters of large adult pines. Recruitment of seedlings was observed at Mullions Range and has also been recorded at Newnes and Lidsdale during a previous study (Williams and Wardle 2007b). This pattern of invasion is consistent with spread patterns in South Africa where seedlings establish around isolated colonists at long distances from the source (Richardson and Brown 1986) and indicates that wildlings are capable of establishing a self-sustaining population. Dispersal of seed from secondary seed sources, known as isolated foci, can speed up the overall rate of invasion (Moody and Mack 1988).

The high percentage of reproductive wildlings at Newnes can be explained by the presence of a species other than *P. radiata*, which was not identified until after the survey had taken place. *Pinus ponderosa* is prevalent throughout the most heavily invaded area and is contributing to the high number of cones present. The species is thought to be more invasive than *P. radiata* (personal communication N. Westman 2005). Indeed at Newnes, *P. ponderosa* wildlings appear to be producing more cones. Other species including *P. contorta* are also more invasive than *P. radiata*. Within Kosciusko National Park 60% of wildlings are *P. contorta*, a species that makes up only 5% of the source plantation (Leaver 1983, Spate *et al.* 1986 in Kasel 2004).

Limitations and future studies

The infestation index represents only the level of pine infestation in the land immediately surrounding the plantation, which may be limiting the accuracy of our results. Isolated pines are known to establish at long distances from the plantation both in Australia (Williams and Wardle 2005) and elsewhere (Richardson and Brown 1986) and are unlikely to be detected using this survey method. For this reason our technique is likely to have underestimated the area of land invaded by pines. Remote sensing techniques such as aerial photograph interpretation or satellite imagery may be more effective for assessing landscape spread of alien plants. For example, Landsat imagery has been successfully used to map *Acacia longifolia* ssp *sophorae* over large areas in Victoria (Emeny *et al.* 2006). Such techniques could easily be applied to map and monitor invasions of *P. radiata* and would also assist in determining the influence of topography and vegetation type on invasion success. Monitoring wildling populations from the air is possible as the crown and tone of *P. radiata* distinguishes the species from native eucalypt vegetation. Aerial surveys have been used previously to assess crown health in plantations (Sims *et al.* 2007) and were used to map pines in an area south west of the Mannus plantation (personal communication J. Molloy).

Despite these limitations, the infestation index remains a useful tool for quickly determining the level of invasion and was necessary to enable a landscape scale investigation. Maps of invaded plantation sites provide a snapshot representation of the current level of infestation within NSW and can help prioritize sites for control. The index itself will allow an assessment of changes in the level of infestation over time. The first two quantitative components of impact of this species, i.e. its geographic extent and a range in abundance of the invader across sites (Parker *et al.* 1999), have been established. A quantification of the third component of impact; effect per individual (Parker *et al.* 1999), is required for a complete quantification of the impact of pines in NSW.

Whilst highly invaded areas may not necessarily be inherently more invasible (Richardson and Pyšek 2006), an examination of the factors that separate invaded and uninvaded sites will help identify some of the variables influencing pine success. The plantations included in this analysis range in age and size, two factors likely to influence the level of seed input into the adjacent vegetation at a site. The well-documented importance of propagule pressure on invasion success (Lockwood *et al.* 2005, Von Holle and Simberloff 2005) suggests that variations in the level of invasion between sites may be due to variation in the size and residence time of the seed source. An analysis of the relationship between plantation age and the level of invasion will help quantify the lag phase associated with pine invasions and is being prepared in a separate manuscript. Other contributing factors known to influence pine success include wind direction (Minko and Aeberli 1986), topography (Ledgard and Langer 1999), level of disturbance (Richardson and Bond 1991), and habitat type (Higgins and Richardson 1998). A closer investigation of how these factors vary across the plantations in NSW will aid attempts to predict future invasion events.

Implications for control

There are a number of successful control measures available for wildling pines, including mechanical removal, chemical treatment and fire (Pryor 1991, Gill and Williams 1996). Details of these techniques as well as procedures for the prevention of pine invasions have been reviewed elsewhere (Ledgard and Langer 1999, Williams and Wardle 2007a). The type of control method used will depend on the density of the infestation and size/age of the pines (DOC 2001). The infestation index developed during this study can immediately help direct control efforts because it has been used to map pine densities surrounding all the major *P. radiata* plantations in the state. We can use the index to make recommendations on the type of control action to be employed in areas experiencing varying levels of invasion (Table 6).

Observations in recently burnt areas suggest that hazard reduction burns are capable of destroying pines less than 1 m in height (Williams unpublished data)

Table 6. Control actions required based on the level of invasion.

Infestation index	Action	Priority	Use of fire
0–1	Monitor every five years after plantation reaches reproductive age: 20 years	Low	Prescribed burns are an effective control measure
2–3	Remove wildlings. Monitor every 5–10 years after control has taken place.	Medium	Follow up control within five years of all fires. Fell reproductive wildlings prior to burning
4–5	Remove wildings. Monitor every 5–10 years after control has taken place.	High	

and hence may be used to control wildling populations when pine densities and basal area are low, i.e. in areas with infestation indices of 0–1. Areas with infestation indices of 3 or above contain pines more than 10 m tall, which typically bear cones (personal observations M. Williams). Fire can stimulate cone opening and seed release (Richardson and Brown 1986, Williams and Wardle 2007a) making it unsuitable as a control tool in reproductive populations. Cut and burn strategies have been used effectively in South Africa (Richardson and Brown 1986) and are recommended in areas where pines are growing at high densities and are already reproductive. Final site selection and prioritization for control requires an assessment of the biodiversity value of the areas invaded.

In summary, the varying levels of invasion across the NSW plantations, including the discovery that many locations remain uninvaded, suggests that there is time and opportunity to implement effective control. It is clear that taking a spatial approach was needed to prioritize areas of concern and contributes to our general understanding of the variable success of invaders across the landscape.

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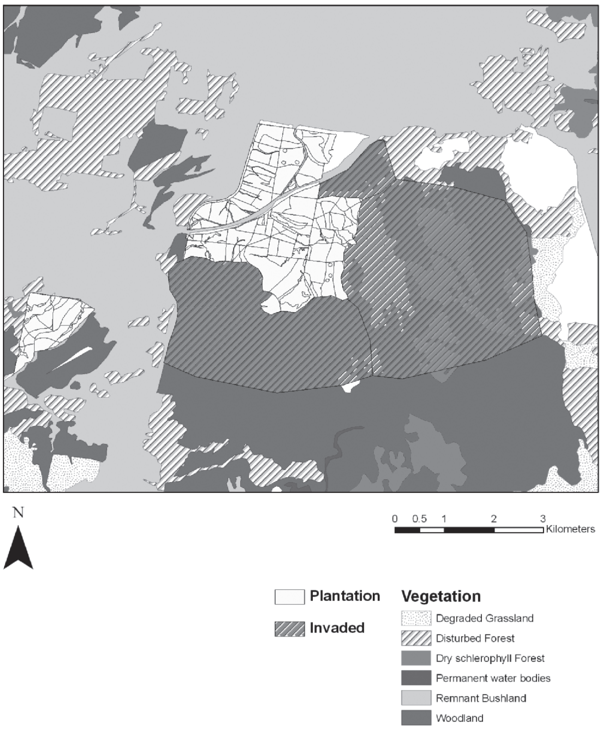
Appendices

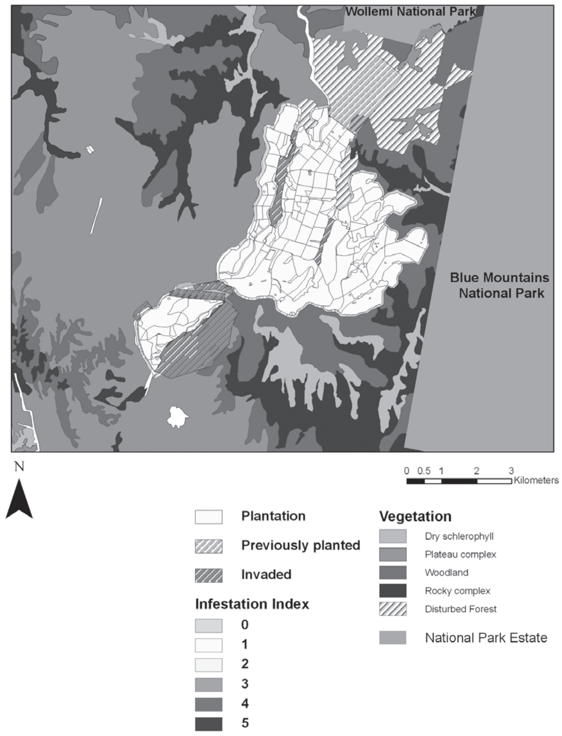
See next pages.

Please note

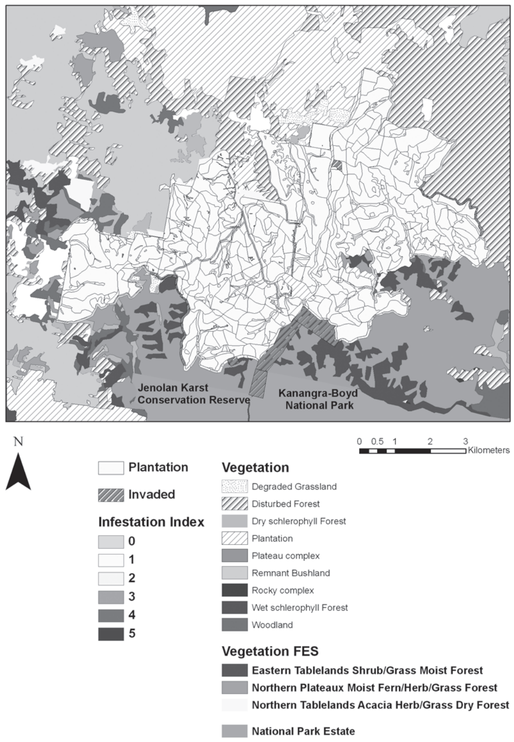
Full colour appendices can be found at http://hdl.HANDLE.NET/2123/2761.



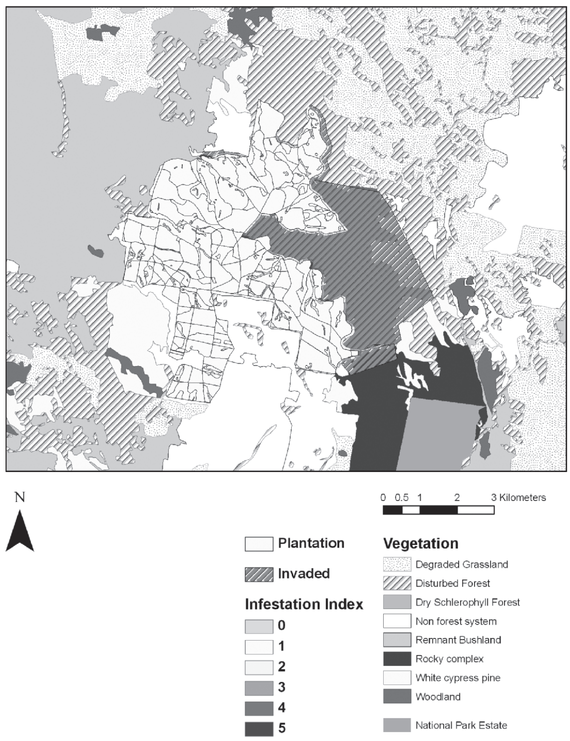
Appendix 1. ***Pinus radiata*** **invasion at Lidsdale State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (Eastern Bushlands, Holme 1993).**



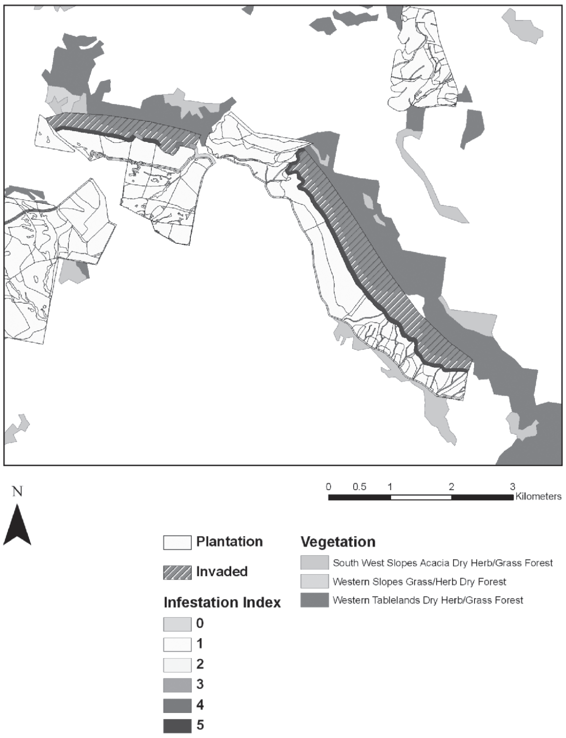
Appendix 2. ***Pinus radiata*** **invasion at Newnes State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (Eastern Bushlands, Holme 1993).**



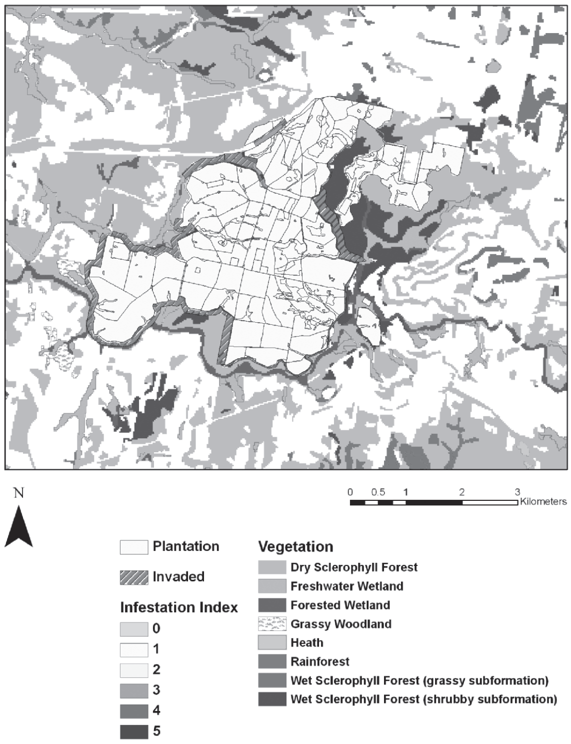
Appendix 3. ***Pinus radiata*** **invasion at Jenolan State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (Forest Ecosystems South Coast; Thomas** ***et al.*** **2000 and Eastern Bushlands, Holme 1993).**



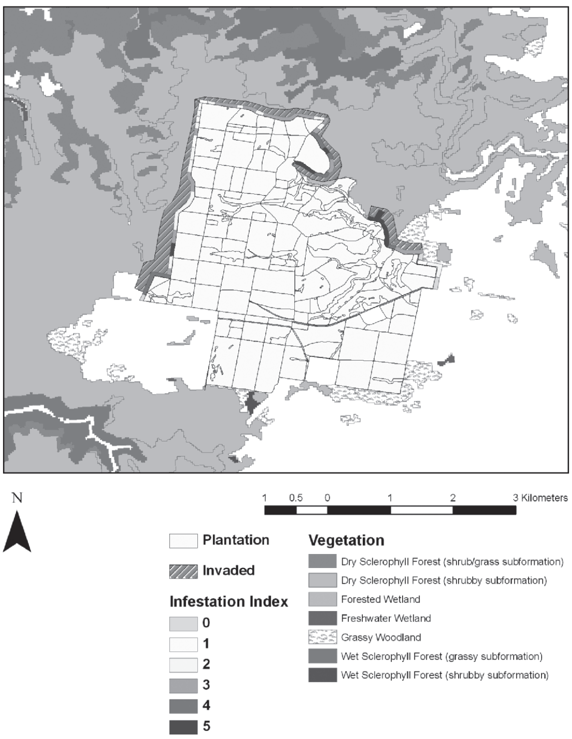
Appendix 4. ***Pinus radiata*** **invasion at Mullions Range State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (Eastern Bushlands, Holme 1993).**



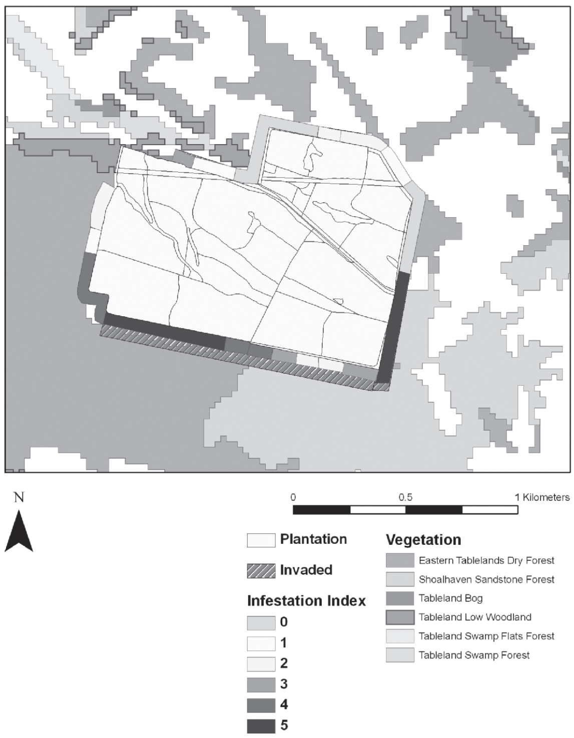
Appendix 5. *Pinus radiata* invasion at Mannus State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (Forest Ecosystems South Coast, Thomas *et al.* 2000).



Appendix 6. *Pinus radiata* invasion at Penrose State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (South-east NSW, Tozer *et al.* 2006).



Appendix 7. *Pinus radiata* invasion at Belangelo State Forest. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (South-east NSW, Tozer *et al.* 2006).



Appendix 8. *Pinus radiata* invasion at Wingello B. Plantation data are provided by Forestry NSW. Vegetation data are provided by Department of Environment and Conservation (South-east NSW, Tozer *et al.* 2006).