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Fuel manipulation with herbicide treatments to reduce fire hazard in young pine (*Pinus elliottii* × *P. caribaea*) plantations in south-east Queensland, Australia

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Abstract. Wildfire represents a major risk to pine plantations. This risk is particularly great for young plantations (generally less than 10 m in height) where prescribed fire cannot be used to manipulate fuel biomass, and where flammable grasses are abundant in the understorey. We report results from a replicated field experiment designed to determine the effects of two rates of glyphosate (450 g L^{-1}) application, two extents of application (inter-row only and inter-row and row) with applications being applied once or twice, on understorey fine fuel biomass, fuel structure and composition in south-east Queensland, Australia. Two herbicide applications (~9 months apart) were more effective than a once-off treatment for reducing standing biomass, grass continuity, grass height, percentage grass dry weight and the density of shrubs. In addition, the 6-L ha^{-1} rate of application was more effective than the 3-L ha^{-1} rate of application in periodically reducing grass continuity and shrub density in the inter-rows and in reducing standing biomass in the tree rows, and application in the inter-rows and rows significantly reduced shrub density relative to the inter-row-only application. Herbicide treatment in the inter-rows and rows is likely to be useful for managing fuels before prescribed fire in young pine plantations because such treatment minimised tree scorch height during prescribed burns. Further, herbicide treatments had no adverse effects on plantation trees, and in some cases tree growth was enhanced by treatments. However, the effectiveness of herbicide treatments in reducing the risk of tree damage or mortality under wildfire conditions remains untested.

Additional keywords: fuel loading, fuel structure, plantation management, plant composition, tree growth, wildfire risk.

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Introduction

Wildfire represents a great threat to exotic pine plantations in Australia and a high economic risk to timber companies in many parts of the world (e.g. Dodge 1972; Byrne 1980; Marty and Barney 1981; Hunt *et al.* 1995; Mercer *et al.* 2007). In south-east Queensland, Australia, this risk has increased in recent years with a higher incidence of deliberately lit fires associated with increasing urbanisation, particularly around the Beerburrum estate, which is ~60 km north of Brisbane (Christensen 2006). Thus plantation managers are under pressure to ensure that the resource is adequately protected from wildfire.

Low-intensity prescribed fire is commonly used in pine forests to reduce accumulation of flammable understorey vegetation in subtropical Australia (Byrne 1980; Hunt and Simpson 1985; Hunt and Crock 1987) and elsewhere (e.g. Biswell 1960; Wade and Johansen 1986; Pyne *et al.* 1996), although it is less commonly used in certain fire-sensitive pine forests, particularly in young stands. Young plantations, generally less than 7 years old, in south-east Queensland are not normally subjected to prescribed fire owing to the high risk of scorch, stem damage, loss of growth and mortality even under appropriate planned burning (fuel and weather) conditions (Wade and Johansen 1986; Burrows *et al.* 1989). Without alternative management of understorey vegetation, young pine plantations are particularly vulnerable to damage from fire. This is because before canopy development, sunlight reaching the forest floor encourages growth of understorey vegetation (e.g. perennial grasses like *Imperata cylindrica*), which can increase the flammability potential (Platt and Gottschalk 2001; Vilà *et al.* 2001) and so the understorey vegetation of young plantations can be more hazardous than that of pine plantations that have reached canopy closure (Hunt and Crock 1987). In addition, reduced planting densities have resulted in altered understorey vegetation composition in pine plantations, with increased abundance of flammable grasses and understorey shrubs (Hunt and Crock 1987). Vulnerability is potentially also increased in second-rotation plantations, because post-harvest trash retention can lead to higher surface fuel biomass at the time of planting (Agee and Skinner 2005).

Herbicide application to the understorey vegetation represents an alternative method of fuel manipulation to reduce fire hazard in young pine plantations not yet mature enough to allow prescribed burning. Herbicide treatment has been considered as an alternative technique for managing hazardous forest fuels and has been predicted to reduce fire intensity for 2–6 years following treatment (Brose and Wade 2002). However, the applicability of these predictions from a mature pine forest in Florida (from Brose and Wade 2002) to young pine plantations in southern Queensland is uncertain as the effectiveness of herbicide treatments can be influenced by the type and rates of herbicide used, the understorey vegetation composition, weather conditions and soil type (Miller and Miller 2004). For example, effectiveness of glyphosate treatments may only last one growing season in some cases (e.g. Wagner *et al.* 1999; Jylhä and Hytönen 2006).

Glyphosate is a systemic broad-spectrum herbicide that is used extensively in forestry management as it has low toxicity to non-target organisms and is inactivated by adsorption to clay minerals in the soil (Sprankle *et al.* 1975*a*, 1975*b*; Veiga *et al.* 2001; Shepard *et al.* 2004; Tatum 2004). However, a goal for many forestry companies is to decrease their reliance on herbicide use to reduce potential environmental impacts on non-target species and the cost of treatments. Using lower rates of application may be one option considered to minimise herbicide use for fire risk management. Current grass weed control in the southern Queensland pine estates generally involves glyphosate ($450\,\mathrm{g\,L^{-1}}$) applications at $6\,\mathrm{L\,ha^{-1}}$ (A. Britcliffe, Forestry Plantations Queensland, pers. comm., 2008) but effectiveness of rates lower than this has not been thoroughly examined. Another method of reducing herbicide usage is to only apply it to the inter-row zones of a plantation. This may be desirable as the application of herbicide is less likely to contact the lower tree branches and reduce tree growth. Inter-rows contain the majority of fuels in a given plantation (i.e. they make up most of the area), and hence reducing fuel hazard in the inter-rows should help reduce the spread of a wildfire and assist in wildfire suppression. However, this pattern of herbicide application may not be as successful in reducing the potential fire damage to young trees, because significant fuels can accumulate in the tree rows and encourage the vertical spread of fire into the tree canopy (Kilgore and Sando 1975; Raymond and Peterson 2005; Battaglia *et al.* 2008), effectively increasing the probability of scorch and tree mortality.

The effects of different management techniques to alter fuel structure and composition and reduce fire hazard have been widely reported (e.g. Stephens 1998; Brose and Wade 2002; Raymond and Peterson 2005; Stephens and Moghaddas 2005; Battaglia *et al.* 2008). However, there is little published information on the potential changes in fuel biomass, composition and structure following herbicide treatments. To investigate herbicide application as a fuel manipulation technique in young *Pinus elliottii* × *P. caribaea* plantations, we established a replicated field experiment in south-east Queensland, Australia. Specifically, we aimed to determine whether effective fuel reduction can be achieved through herbicide application, and if so whether: (1) using a lower rate of application ($3\,\mathrm{L\,ha^{-1}}$ rather than $6\,\mathrm{L\,ha^{-1}}$), a single application as opposed to two applications and a lesser extent of application (inter-rows only rather than inter-row and row treatment) are effective in reducing fuel biomass and fire hazard; (2) there are any non-target effects of herbicide treatments on tree growth and (3) herbicide treatments reduce the tree scorch during prescribed burning.

Methods

Study site description

The experiment was established at three sites in the Beerburrum plantation estate, referred to as: Blackswamp (latitude: −26°53′07.46″, longitude: 153°00′35.67″), Tripconys (latitude: −26°58′59.23″, longitude: 153°01′51.74″) and Donnybrook (latitude: −26°59′10.55″ longitude: 153°00′44.73″). Sites were typical of young plantations (*Pinus elliottii* var. *elliottii* × *P. caribaea* var. *hondurensis*, F1 hybrid plantations, 4–5 years since planting) in the estate where blady grass (*Imperata cylindrica*) is the dominant understorey fuel type. Prior to experimental establishment, each site had received routine silvicultural management (e.g. post-planting weed control and fertiliser addition). All sites were second-rotation plantations that were strip-ploughed before planting. Sites were planted in December 2002 (Donnybrook), January 2003 (Tripconys) and July 2003 (Blackswamp). Average annual rainfall for the area is 1380 mm (Beerburrum Forestry Office), with most rainfall occurring through summer months.

Each site was split into two blocks: one that was subjected to prescribed fire in May 2010, and the other that remained unburnt (Fig. 1). The experiment was a split-plot design with nine herbicide treatments in each block (Fig. 1). Treatments were: (1) two herbicide applications at $6\,\mathrm{L\,ha^{-1}}$ over inter-rows and rows; (2) one herbicide application at $6\,\mathrm{L\,ha^{-1}}$ over inter-rows and rows; (3) two herbicide applications at $6\,\mathrm{L\,ha^{-1}}$ over inter-rows only; (4) one herbicide application at $6\,\mathrm{L\,ha^{-1}}$ over inter-rows only; (5) two herbicide applications at $3\,\mathrm{L\,ha^{-1}}$ over inter-rows and rows; (6) one herbicide application at $3\,\mathrm{L\,ha^{-1}}$ over inter-rows and rows; (7) two herbicide applications at $3\,\mathrm{L\,ha^{-1}}$ over inter-rows only; (8) one herbicide application at $3\,\mathrm{L\,ha^{-1}}$ over inter-rows only; and (9) no herbicide application (control). In total there were 54 sampling plots (nine herbicide treatments × two fire treatments × three sites).

Each treated area was at least 100 m in length and with a minimum width of four tree rows (Fig. 1). The measure plot consisted of the two inter-rows (~4 m wide) and rows in the centre of each treatment area.

A description of the stands before treatments in 2007 is provided in Table 1. Crown closure was not achieved over the course of this study at any of the sites (it is expected to occur when these forests are 10–12 years in age).

Application of treatments

The initial herbicide treatment was carried out in late January 2007 and the repeat applications carried out in early November 2007. The herbicide (glyphosate $450\,\mathrm{g\,L^{-1}}$) was applied

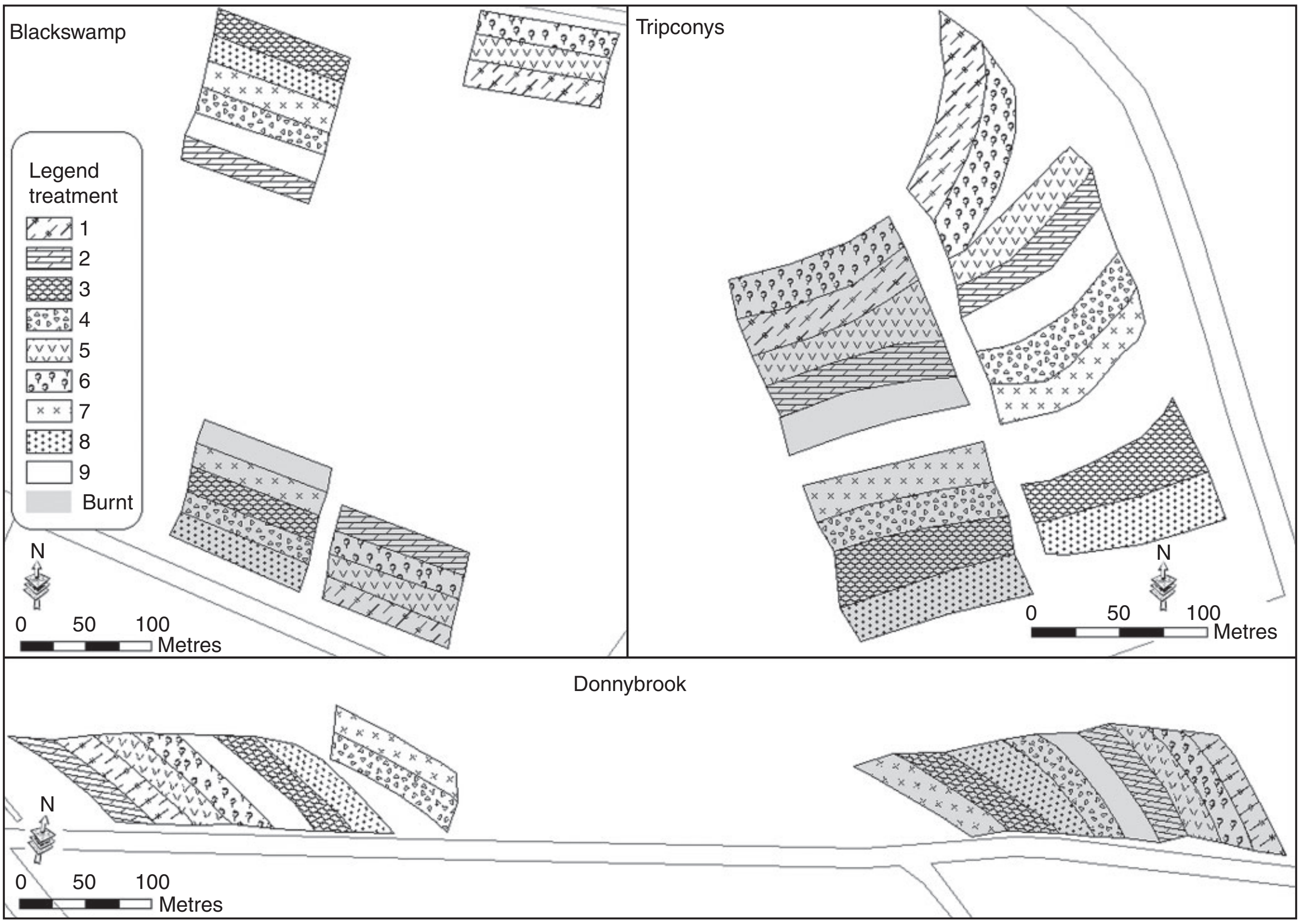

Fig. 1. Experimental layout at the three sites (Blackswamp, Tripconys and Donnybrook) located in the Beerburrum pine plantation estate, Queensland, Australia. Treatment labels are: (1) two herbicide applications at 6 L ha^{-1} over inter-rows and rows; (2) one herbicide application at 6 L ha^{-1} over inter-rows and rows; (3) two herbicide applications at 6 L ha^{-1} over inter-rows only; (4) one herbicide application at 6 L ha^{-1} over inter-rows only; (5) two herbicide applications at 3 L ha^{-1} over inter-rows and rows; (6) one herbicide application at 3 L ha^{-1} over inter-rows and rows; (7) two herbicide applications at 3 L ha^{-1} over inter-rows only; (8) one herbicide application at 3 L ha^{-1} over inter-rows only; and (9) no herbicide application (control). Grey shaded blocks at each site were subjected to prescribed burning in May 2010.

Table 1. Stand description for the *Pinus elliottii* × *P. caribaea* plantation sites before treatments in 2007

Means (±standard errors) were calculated across all treatments at each site. For heights and diameter at breast height (DBH), means were calculated for all trees in all plots ($n = 1150$, 976, 905 for Blackswamp, Tripconys and Donnybrook) whereas density, basal area and fuel load means were calculated across the 18 plots at each site. Basal areas were derived for each plot from DBH measures by summing individual tree basal areas for all trees in a plot

Descriptor	Blackswamp	Tripconys	Donnybrook
Height (m)	5.2 ± 0.02	6.9 ± 0.03	5.8 ± 0.05
DBH (cm)	8.0 ± 0.05	11.8 ± 0.06	9.5 ± 0.10
Density (number of trees per hectare)	644 ± 7.50	545 ± 16.9	530 ± 12.4
Basal area (m^2 ha^{-1})	3.4 ± 0.16	6.0 ± 0.21	4.0 ± 0.19
Total inter-row fine-fuel load (standing and litter)	14.9 ± 0.82	11.7 ± 0.64	9.9 ± 0.45

with a tractor-mounted box sprayer. A surfactant (1020 g L^{-1} polyether-modified polysiloxane) was added at a rate of 2 mL L^{-1} to improve penetration and translocation of glyphosate. The box sprayer was calibrated before treatments.

Prescribed burn treatments were conducted across 2 days in May 2010 by forestry operational staff. Weather conditions were similar during burns on both days. Temperatures during the burns varied from 20 to 26°C, relative humidity varied from 35 to 55% and there was a light (5 km h^{-1}) breeze on both occasions. Flame heights during the burns were generally $\leq$0.5 m. Burns were of low intensity (<550 kW m^{-1}) and were mostly patchy in nature. At the time of prescribed burning, canopy base height varied from 1.5 to 3.5 m and there was a clear gap between the surface fuels and the tree canopy.

Fuel biomass, composition and structure sampling

We measured the biomass of fine herbaceous fuels, which are particularly important for predicting fire behaviour because these fuels burn rapidly when dry (Walker 1981; Cheney *et al.* 1998; Catchpole 2002). Fuel biomass samples were collected from plots in December 2006 (pretreatment), May 2007, October 2007 (before repeat application), March 2008, October 2008, April 2009 and February 2010. At set points along a transect in each plot, standing fuel loads were categorised as high, moderate or low and one representative sample was collected from each category per plot. Categorisation of standing fuels was based on standing fine-fuel height and density and involved initially traversing the plot to ensure each category could be clearly distinguished by the assessors. Assessments were made at 5-m intervals along two 40-m transects (16 sampling points in the inter-rows of each plot), with one transect running along each inter-row area of the measure plot. Transects were located >10 m from the plot edge. The same transects were sampled on successive occasions. Assessments in the rows were made at eight points either side of the 40-m inter-row transects. Row measurements were only made in the areas where row treatments were applied and in the control areas.

Sampling involved collecting all fuels <0.6 cm in diameter from within 0.5 × 0.5-m quadrats and dividing samples into standing biomass (i.e. standing plant material) and litter (i.e. pine needles, bark, twigs and non-attached grass). Litter biomass was only collected from one block at each site. Samples were oven-dried at 75°C to a constant weight and weighed. Sample weights were converted to provide an estimate of tonnes of fuel per hectare. Standing fuel biomass for each plot was estimated based on the proportion of high, moderate or low fuel loads for each plot and the sample weights (i.e. if 70% of the plot was categorised as high fuel load, then fuel biomass for the high standing-fuel sample was multiplied by this proportion). Using a Spearman rank test and Student's *t*-statistic to test if correlations differed significantly from zero, we found that there was significant correlation between standing biomass and fuel load categories ($t = -9.04$, d.f. $= 574$, $P < 0.001$). However, there was no significant correlation between litter biomass and standing fuel load categories ($t = -0.69$, d.f. $= 484$, $P = 0.49$), so litter biomass was estimated by calculating an average for the three independent samples in each plot.

Measures of understorey plant composition and structure were made in December 2006, May 2007, March 2008, April 2009 and February 2010. Understorey composition was assessed at each site by recording the most abundant fuel constituents in 0.5 × 0.5-m quadrats along the same transects used to assess fuel loads. This involved ranking the three most dominant species (in terms of estimated dry weight) in each quadrat. The dry-weight-rank method was used to estimate the botanical composition of each site on a dry-weight basis (Mannetje and Haydock 1963). The total number of first, second and third rank scores for each species was tallied across inter-rows and rows and then multiplied by a constant. The constants used were 8.04 for rank one, 2.41 for rank two and 1.0 for rank three, as recommended by Mannetje and Haydock (1963), where the three ranks are not all filled in one or more quadrats. The products obtained were then summed to give a score, and the scores were expressed as a percentage of the sum of all scores to give an estimate of dry-weight percentage for each species. The constants are derived from the empirical relationship between actual and ranked dry-weight composition of pasture, and have been found to provide good estimates for a wide range of pasture types and compositions (Mannetje and Haydock 1963; Walker 1976; Tothill *et al.* 1978). Prior to analysis, herbaceous species were divided into grasses (taxa in the family Poaceae), forbs (small-growing dicotyledonous species), other monocots (monocotyledonous species that do not belong to Poaceae) and ferns (mostly bracken fern, *Pteridium esculentum*). Woody plants (shrubs) greater than 1 m in height were counted in the 5-m distance between assessment points on each of the above-mentioned transects (number per 20 m^2) and were summed for each plot to give a number over 320 m^2 (16 × 20 m^2). Shrub density in the rows was counted in a 10 × 2-m area around each assessment point (5 m along the row either side of the assessment point, with a row-width of 2 m) and these densities were summed for each plot to give a number over 160 m^2 (8 × 20 m^2).

Along the plot transects, we also recorded the height of the dominant standing grass fuel and litter depth, which was measured as the depth of material from the mineral soil surface to the top of the litter layer (i.e. including the decomposing material in the 'duff' layer and undecomposed organic material). We measured discontinuity of grassy fuels in the 5-m distance between each transect sampling point. Discontinuity was ranked on a four-point scale as: 1, continuous (uniform coverage of grass with no obvious gaps); 2, moderately continuous (gaps between grasses, but gaps smaller than the height of the surrounding grass); 3, moderately discontinuous (large gaps between grasses, with gaps larger than the surrounding grass height); and 4, discontinuous (very sparse or no grass cover).

Plantation tree growth sampling

Diameter at breast height (DBH, at 1.3 m, over bark) and height of all trees in each plot was measured at the beginning of the experiment (pretreatment, January 2007) and subsequently in July 2010. Scorch height was measured for trees in the blocks that were burnt in May 2010. Average scorch height was measured on the bole of each tree. Total height and scorch height were measured using graduated height sticks to the nearest decimetre and DBH was measured with a tape to the nearest millimetre.

Analysis

Statistical analysis was carried out in *GENSTAT* (11th edition, VSN International Ltd, UK). Repeated-measures ANOVA with a Greenhouse Geisser adjustment was used to analyse fuel biomass (standing and litter) and the vegetation composition (percentage dry weights of grass, forbs and other monocots) and structure (grass height, grass discontinuity, litter depth and shrub density) data because the same areas were assessed at each sampling time. Separate analyses were carried out for the inter-rows and rows because fuel composition and structure were predicted to vary between rows and inter-rows owing to potential effects of soil disturbance in the rows and variation in tree canopy cover between these two zones. Herbicide treatments had no significant effect on litter depth in either the inter-rows or rows, so results for this variable are not reported.

For the inter-row analyses, the treatment design was factorial (2 × 2 × 2) with an added control. Thus the treatment structure was specified as: herbicide/(rate of application × number of applications × zone of applications), where herbicide was a factor (i.e. with or without herbicide). The blocking structure was specified as: site/block/plot. Fuel load, composition and structure data were analysed before the burning treatment. Hence the two blocks at each site effectively received the same treatments. Analysis was similar for the rows; however, inter-row treatment plots were not included in the analysis (i.e. there was no zone of application effect). Means and least significant differences (l.s.d.) are reported, with separate least significant differences for comparisons between the non-control treatments and for comparisons with the control. For the fuel biomass data, there were six repeated-measures as the pretreatment measure in 2006 was initially treated as a covariate. In this case, the covariate effects were not significant, so the pretreatment data were excluded from the subsequent analysis. For the fuel composition and structure data, there were five repeated-measures and the pretreatment data were included as a covariate. Shrub density was transformed with a $\ln(x)$ transformation and plant compositional data (percentage dry weights) were transformed using an $\arcsin\left(\sqrt{P/100}\right)$ transformation before analysis.

We analysed change in tree diameter and height between the pretreatment and 2010 measure using ANOVA. Scorch height was also analysed with ANOVA. In these analyses, the experimental unit was a plot of trees and given there were unequal numbers of trees per plot, the analysis was based on plot means.

Results

Fuel biomass

Herbicide treatments significantly reduced standing fine-fuel biomass in the inter-rows and rows (Tables 2, 3). In the inter-rows, there was a significant interaction between number of applications and zone of application (Table 2). The single-application treatments had higher standing fuel biomass where applied to the inter-rows only than where applied to the inter-rows and rows, but where herbicide treatments were applied twice, the inter-row-only treatment had lower standing biomass than the inter-row and row treatment (Table 2). There was also a significant interaction between sampling time and the number of applications. In the control treatment, standing biomass increased until October 2008 before declining to below pretreatment levels in February 2010, whereas in the repeated-application treatments, standing biomass declined rapidly between October 2007 and March 2008, following the second herbicide application, and then continued to decline gradually thereafter (Fig. 2*a*). In the inter-rows, the higher rate of application resulted in a marginal reduction in standing biomass relative to the lower rate of application (Table 2). Rate of application was also significant in the rows, again with lower standing biomass in the 6-L ha^{-1} treatment than the 3-L ha^{-1} treatment (Table 3). Number of applications was also important in the rows, with lower standing biomass where treatments were applied twice (Table 3). However, in the rows, there was no significant difference between the lower rate of application and the control or between the single-application treatment and the control. Across all treatments, there was also a significant decline in standing biomass through time in the row zone (Appendix 1).

Herbicide treatments had no significant influence on litter biomass in the inter-rows (Table 2). In the rows, the repeated-application treatments did result in lower litter biomass than the single-application treatment, although there was no difference among treatments and the control (Table 3). There was a significant time by application rate interaction in the rows, due to a decline in litter biomass in the repeated-application treatment immediately following the second treatment, but an increase in litter biomass in other treatments (Fig. 2*b*). Variation in litter biomass over time was significant but fluctuated somewhat erratically in the inter-rows. In the rows, litter biomass increased approximately two-fold between the first (mean ± s.e. in May 2007, 3.7 ± 0.28 t ha^{-1}) and last (February 2010, 7.4 ± 0.28 t ha^{-1}) measurements.

Fuel structure and composition

In both the inter-rows and rows, grass height was significantly lowered owing to application of herbicide (Tables 2 and 3). Number of applications had a significant influence on grass height, two applications being more effective than a single application in reducing grass height in the inter-rows and rows (Tables 2 and 3). In the inter-rows, the single-application treatments were effective in reducing grass height relative to the control, but in the rows, there was no difference between the single-application treatments and the control (Tables 2 and 3). There was a significant time by number of applications interaction. As time progressed, the effectiveness of the single-application treatment was less apparent in both the inter-rows and rows, such that 36 months after the first application, there was little difference in grass height among treatments (Fig. 3*a*; Appendix 1*b*).

In the inter-rows and rows, grass discontinuity was significantly influenced by herbicide application (Tables 2 and 3). Grass discontinuity varied depending on the number of applications and the rate of application in the inter-rows (Table 2). Two applications were more effective in increasing grass discontinuity than a single application and the 6-L ha^{-1} rate was more effective in increasing grass discontinuity than the 3-L ha^{-1} rate (Table 2). The single application and the lower rate of application were more effective in increasing grass discontinuity relative to the control (Table 2). In the rows, the number of applications was also important, again with the repeated application being more effective in increasing grass discontinuity, but the single application was not more effective than the control (Table 3). In the inter-rows, there was a significant time by number of applications interaction. Grass discontinuity fluctuated over time, but these fluctuations were not consistent among treatments (Fig. 3*b*). In the rows, there was a significant time by herbicide treatment interaction. There was a gradual increase in grass discontinuity over time in the control but a more rapid initial increase in grass discontinuity in the herbicide-treated areas (Appendix 1*c*).

Herbicide treatments resulted in a significant reduction in percentage grass dry weight (Table 4). Grass dry weight was lower in the treatments that received two applications than in the treatment that received a single application but there was no difference between the single-application treatments and the control (Table 4). There was a significant rate of application by zone of application interaction (Table 4) and a time by number of applications interaction. Percentage grass dry weight decreased gradually in the control treatment over time, but in

Table 2. Significant overall treatment effects and interactions from analysis of fine-fuel biomass variables (standing and litter), grass height, grass discontinuity score and shrub density (number of shrubs over 320 m^2) in the inter-rows

Rates of herbicide application were 3 and 6 L ha^{-1}, treatments were applied either once or twice and treatments were applied to either the inter-row and row (IR+R) zone or the inter-row only (IR) zone. Predicted means and least significant differences (l.s.d., where appropriate) are reported. Shrub density means were back-transformed to the original scale of measurement (least significant differences from analysis are not reported for back-transformed data). n.s., not significant

Treatment	Standing biomass (t ha^{-1})	Litter biomass (t ha^{-1})	Grass height (cm)	Grass discontinuity score	Shrub density
Herbicide	$P < 0.001$	n.s.	$P < 0.001$	$P < 0.001$	$P < 0.001$
Untreated control mean	4.11	4.79	55.48	1.65	14.44
Herbicide treated mean	2.71	4.33	38.01	2.21	5.99
l.s.d.	0.53		6.93	0.19	
Rate of application	$P = 0.052$	n.s.	n.s.	$P = 0.017$	$P = 0.041$
3 L ha^{-1} mean	2.88	4.12	39.52	2.13	6.82
6 L ha^{-1} mean	2.54	4.54	36.50	2.29	5.26
l.s.d.	0.35			0.13	
Number of applications	$P < 0.001$	n.s.	$P < 0.001$	$P < 0.001$	$P = 0.001$
One application mean	3.20	4.45	43.01	2.02	7.32
Two applications mean	2.22	4.20	33.01	2.40	4.90
l.s.d.	0.35		4.56	0.13	
Zone of application (Zone)	n.s.	n.s.	n.s.	n.s.	$P = 0.006$
IR mean	2.67	4.37	39.80	2.17	7.03
IR+R mean	2.75	4.29	36.22	2.25	5.10
Number of applications × zone	$P = 0.046$	n.s.	n.s.	n.s.	n.s.
1 × IR mean	3.34	4.65	45.10	1.95	8.29
1 × IR+R mean	1.99	4.26	40.92	2.08	6.48
2 × IR mean	3.07	4.09	34.50	2.39	5.96
2 × IR+R mean	2.44	4.31	31.52	2.41	4.00
l.s.d.	0.50				
Covariate (pretreatment measure)			$P = 0.004$	$P = 0.006$	$P < 0.001$

Table 3. Significant overall treatment effects and interactions from analysis of fine-fuel biomass variables (standing and litter), grass height, grass discontinuity score and shrub density (number of shrubs over 160 m^2) in the tree rows

Rates of herbicide application were 3 and 6 L ha^{-1} and treatments were applied either once or twice. Predicted means and least significant differences (l.s.d., where appropriate) are reported. Shrub density means were back-transformed to the original scale of measurement (least significant differences from analysis are not reported for back-transformed data). n.s., not significant

Treatment	Standing biomass (t ha^{-1})	Litter biomass (t ha^{-1})	Grass height (cm)	Grass discontinuity score	Shrub density
Herbicide	$P = 0.043$	n.s.	$P = 0.018$	$P = 0.005$	n.s.
Untreated control mean	4.62	4.63	55.20	1.72	5.09
Herbicide treated mean	3.94	4.60	44.68	2.03	3.94
l.s.d.	0.66		8.93	0.24	
Rate of application	$P = 0.003$	n.s.	n.s.	n.s.	n.s.
3 L ha^{-1} mean	4.42	4.40	47.09	1.97	3.99
6 L ha^{-1} mean	3.46	4.79	42.38	2.12	3.89
l.s.d.	0.59				
Number of applications	$P < 0.001$	$P = 0.034$	$P = 0.002$	$P < 0.001$	$P = 0.011$
One application mean	4.58	4.92	51.78	1.82	4.76
Two applications mean	3.30	4.27	37.58	2.23	3.25
l.s.d.	0.59	0.60	7.98	0.22	

the herbicide-treated areas, there was an initial significant decrease in grass dry weight following treatments, but a slight increase in grass dry weight after this initial reduction (Fig. 4*a*).

Herbicide treatments significantly increased the percentage dry weight of forbs; two applications resulted in a greater dry weight of forbs than the single herbicide application and the single-application treatments increased forb dry weight relative to the control (Table 4). There was a significant herbicide rate by zone of application interaction (Table 4) and an interaction between time and number of herbicide applications. In the control treatment, forb dry weight increased gradually over time, but in the herbicide treatments, forb dry weight increased rapidly following herbicide application before declining, so that 36 months after the first application, dry weights were similar to the control (Fig. 4*b*). Rate of herbicide application also had a significant effect on the dry weight of other monocots; two

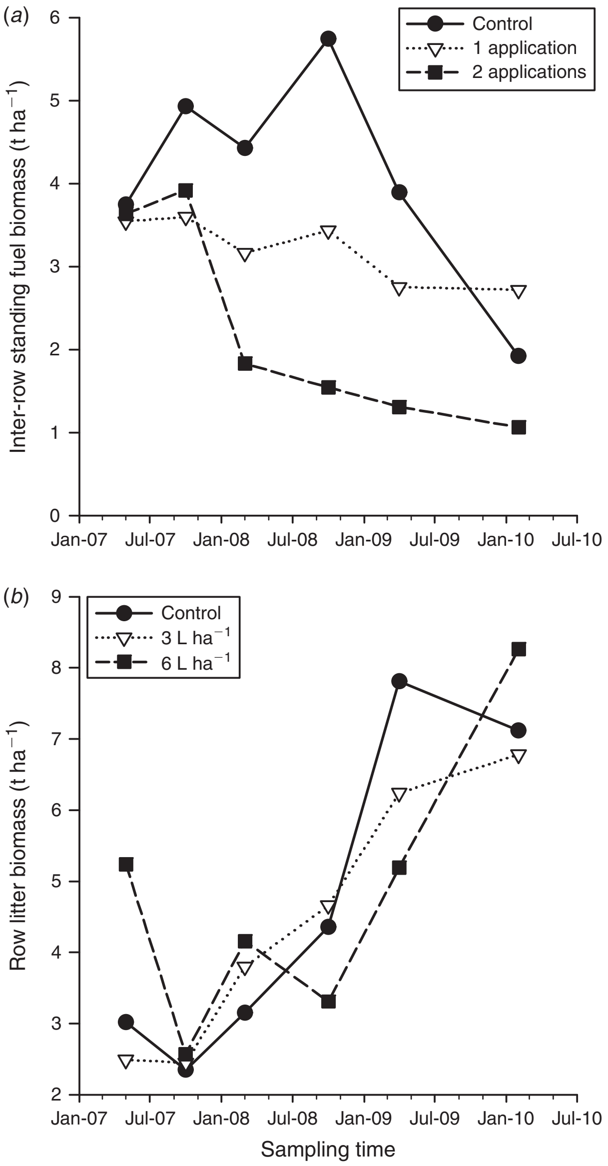

Fig. 2. Trends through time varied among means for: (*a*) single application, repeated application and control treatments for standing fine fuel biomass in the inter-rows; and (*b*) treatments of no herbicide application, the 3-L ha^{-1} rate of application and the 6-L ha^{-1} rate of application for litter biomass in the tree rows. Least significant differences for comparing means were: (*a*) 0.82 for comparing between single and repeated applications and 1.29 for comparisons with the control; and (*b*) 1.42 for comparing between the 3- and 6-L ha^{-1} treatments and 1.74 for comparisons with the control.

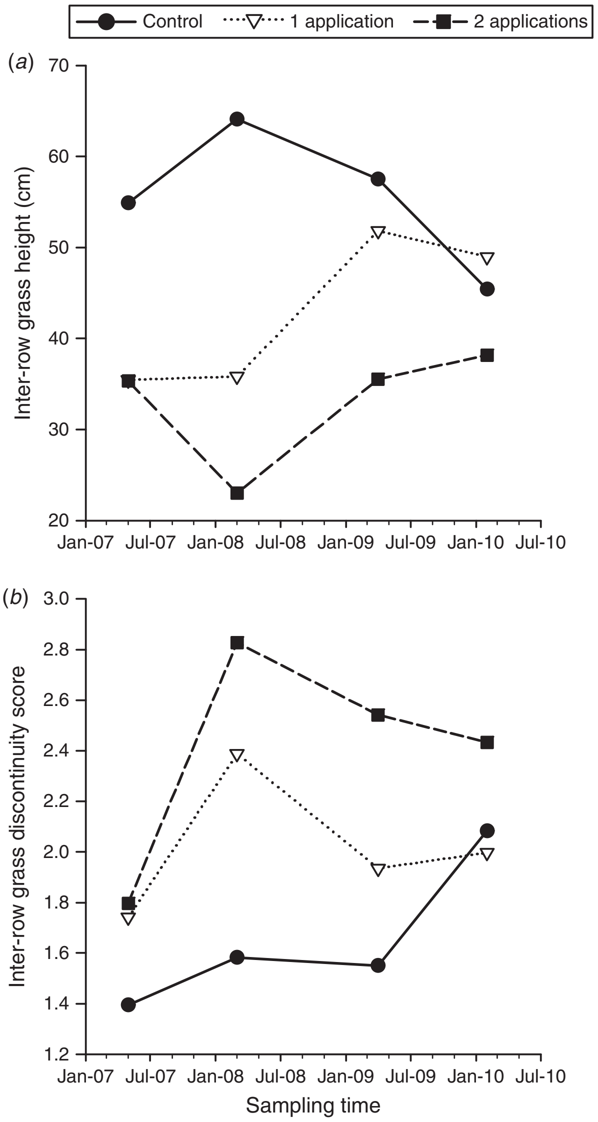

Fig. 3. Trends in covariate adjusted means through time following repeated-measures ANOVA for: (*a*) the inter-row grass height interaction between time and number of applications (least significant differences (l.s.d.) for comparisons between single and repeated applications = 6.84, and for comparisons with the control = 10.81). (*b*) The inter-row grass discontinuity score interaction between time and number of applications (l.s.d. for comparisons between single and repeated applications = 0.26, and for comparisons with the control = 0.42), where higher scores represent greater discontinuity.

herbicide applications increased the dry weight of other monocots relative to one herbicide application, but there was no difference between the single-application treatment and the control (Table 4). Across all treatments, the dry weight of other monocots also increased over time (Appendix 1*d*).

Herbicide application significantly decreased the density of shrubs in the inter-rows (Table 2). Rate of application, number of applications and zone of application all had a significant influence on shrub density in the inter-rows (Table 2). The higher rate of application resulted in lower shrub densities than the lower rate of application; two applications resulted in lower shrub densities than a single application; and the inter-row and row treatments resulted in lower shrub densities than the inter-row-only treatments (Table 2). The lower rate of application, the single rate of application and the inter-row-only application resulted in reduced shrub density relative to the control (Table 2). There was a significant time by number of applications interaction. This was due to a gradual increase in inter-row shrub density in the control and single-application treatment over time, but an initial decrease in shrub density following

Table 4. Significant overall treatment effects and interactions from analysis of percentage dry weight of grasses, forbs and other monocots estimated using the dry-weight-rank method

Rates of herbicide application were 3 and 6 L ha^{-1}, treatments were applied either once or twice and treatments were applied to either the inter-row and row (IR+R) zone or the inter-row only (IR) zone. Data were transformed before analysis but means were back-transformed to the original scale of measurement. Significant differences among means for the 'Rate × Zone' interaction are identified with different superscripts. n.s., not significant

Treatment	% Grass	% Forb	% Other monocots
Herbicide	$P = 0.020$	$P < 0.001$	n.s.
Untreated control mean	76.95	4.14	0.65
Herbicide treated mean	68.97	13.76	0.79
Rate of applications (Rate)	n.s.	n.s.	n.s.
3 L ha^{-1} mean	69.02	12.65	0.88
6 L ha^{-1} mean	69.00	14.13	0.70
Number of applications	$P = 0.006$	$P = 0.002$	$P < 0.001$
One application mean	72.61	11.12	0.36
Two applications mean	66.17	15.89	1.43
Zone of application (Zone)	n.s.	n.s.	n.s.
IR mean	68.30	12.65	0.70
IR+R mean	69.73	14.13	0.88
Rate × Zone	$P = 0.013$	$P = 0.027$	n.s.
3 × IR mean	71.71^{ab}	10.50^{a}	0.87
3 × IR+R mean	67.11^{ab}	15.16^{b}	0.89
6 × IR mean	65.22^{a}	15.16^{b}	0.55
6 × IR+R mean	72.61^{b}	13.08^{ab}	0.87
Covariate (pretreatment measure)	$P < 0.001$	$P < 0.001$	$P = 0.005$

herbicide treatment in the repeated-application treatment (Fig. 4*c*). In the rows, herbicide treatments were less effective in reducing shrub densities (Table 3). Two herbicide applications were more effective than a single application in reducing shrub density in the rows but there was no difference between the single-application treatment and the control (Table 3). Across all treatments, there was also a significant increase in shrub density in the rows over time (Appendix 1*e*).

Plantation tree growth and health

Change in tree DBH over time was significantly influenced by herbicide treatment (Table 5). Number of herbicide applications and zone of application had a significant influence on DBH growth (Table 5). The single-application treatment resulted in less DBH growth than the repeated-application treatment and the broader coverage of application resulted in greater change in DBH growth relative to the lesser coverage of application (Table 5). The single-application treatment and the inter-row-only treatment resulted in greater DBH growth relative to the control (Table 5). Change in tree height over time was marginally influenced by herbicide treatment (Table 5). For change in tree height, there was a significant herbicide rate by zone of application interaction (Table 5). At the 3-L ha^{-1} rate of application, there was a trend of greater height growth in the inter-row and row treatment than the inter-row-only treatment, but at the 6-L ha^{-1} rate of application, this trend was reversed.

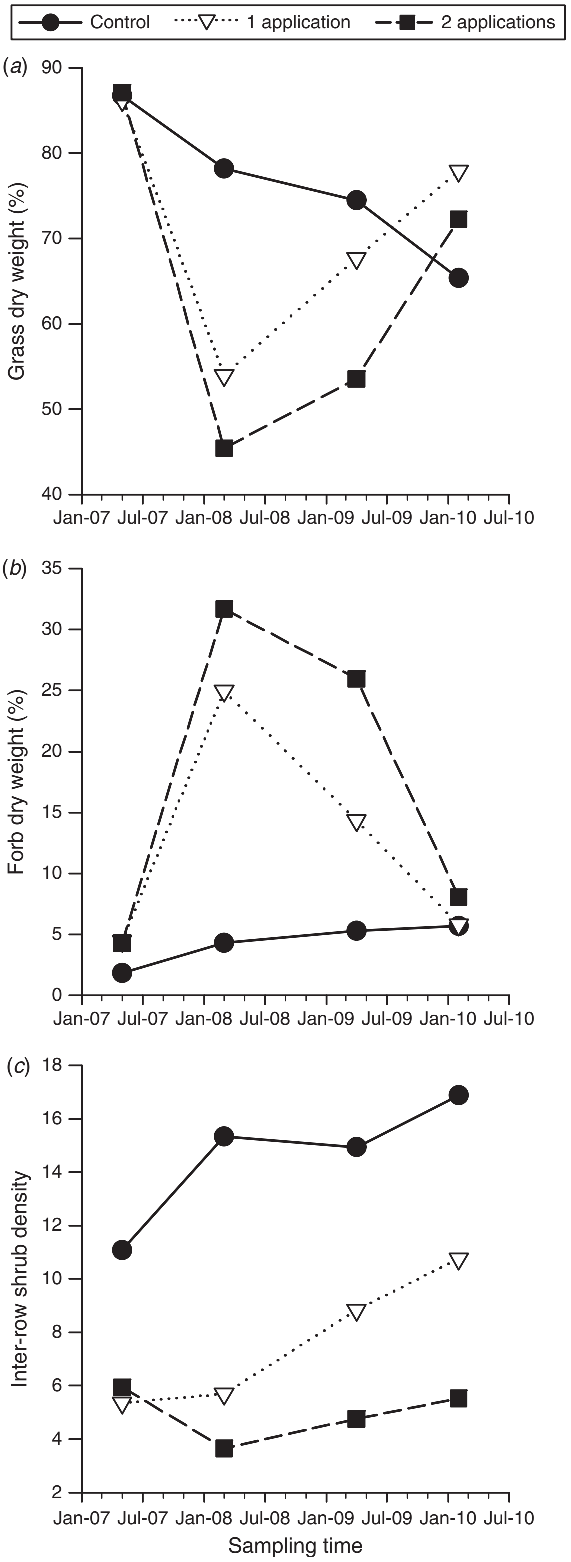

Fig. 4. Trends in covariate adjusted, back-transformed means for significant interactions between time and the number of herbicide applications following repeated-measures ANOVA for: (*a*) percentage grass dry weight; (*b*) percentage forb dry weight; and (*c*) shrub density (number of shrubs per 320 m^2) in the inter-rows.

Table 5. Significant results from ANOVA of change in tree diameter at breast height (DBH) and height growth between 2007 (pretreatment) and 2010 and for scorch height following prescribed burning in 2010 at one block in each site

Rates of herbicide application were 3 and 6 L ha^{-1}, treatments were applied either once or twice and treatments were applied to either the inter-row and row (IR+R) zone or the inter-row only (IR) zone. Predicted means and least significant differences (l.s.d., where appropriate) are reported. n.s., not significant

Treatment	Change in DBH (cm)	Change in height (m)	Scorch height (m)
Herbicide	$P < 0.001$	$P = 0.051$	$P = 0.030$
Untreated control mean	10.03	6.98	5.93
Herbicide treated mean	10.74	7.12	4.03
l.s.d.	0.38	0.14	1.69
Rate of applications (Rate)	n.s.	n.s.	n.s.
3 L ha^{-1} mean	10.66	7.11	3.91
6 L ha^{-1} mean	10.82	7.13	4.16
Number of applications	$P = 0.002$	n.s.	n.s.
One application mean	10.54	7.08	4.19
Two applications mean	10.95	7.16	3.87
l.s.d.	0.26		
Zone of application (Zone)	$P = 0.001$	n.s.	$P = 0.035$
IR mean	10.52	7.15	4.64
IR+R mean	10.96	7.10	3.42
l.s.d.	0.26		1.13
Rate × Zone	n.s.	$P = 0.004$	n.s.
3 × IR mean	10.42	7.06	4.40
3 × IR+R mean	10.91	7.16	3.41
6 × IR mean	10.63	7.23	4.89
6 × IR+R mean	11.02	7.04	3.43
l.s.d.		0.13	

Herbicide treatment significantly reduced tree scorch height during prescribed burning (Table 5). Tree scorch height was significantly influenced by the zone of herbicide application, scorch being greater in the inter-row only treatments than in the inter-row and row treatments (Table 5). There was no significant difference in scorch height between the inter-row-only treatment and the control treatment.

Discussion

Herbicide application in the young plantations studied did reduce hazardous fuels in the period before prescribed burning could be carried out. A modelling study by Brose and Wade (2002) reported similar results, in that herbicide treatments were predicted to decrease fire intensity 2–6 years post treatment in mature forest. However, these authors also suggested that herbicide application could potentially result in pine mortality following prescribed burning in drought conditions due to a greater biomass on the forest floor and subsequent root-kill. Although prescribed burning was not carried out during drought in the current study, there was no evidence of tree mortality following prescribed burning and there was no significant difference in litter biomass among treatments just before prescribed burning. Litter depths were rarely great enough (i.e. >7.5 cm) to allow smouldering fires, which can maintain lethal temperatures for over an hour and result in root death (Beadle 1940; Busse *et al.* 2005; Monsanto and Agee 2008; Varner *et al.* 2009).

An increase in litter biomass was apparent in the tree rows over time. This can be attributed to increased pine-needle litter fall over the course of the study. As the tree canopies developed, there was also a reduction in grass dry weight in the control plots over time and a reduction in standing grass biomass in these plots between 2008 and 2010. Such reductions in grass biomass with increasing tree canopy are widely reported (Jameson 1967; Walker *et al.* 1986; Scanlan and Burrows 1990) and are important for decreasing biomass of standing fine fuels at ground layer in plantations, allowing forest managers to conduct prescribed burns with reduced risk of tree scorch and associated losses in growth rate. In the current study, the inter-row and row herbicide treatments significantly reduced scorch height at the time of the first prescribed burn despite the effectiveness of herbicide treatments being less obvious at this time. Hence, it is likely that an even greater reduction in scorch height could be achieved if prescribed burning was carried out within 24 months of a second herbicide application.

Potential non-target effects of herbicides on tree growth in young plantations are not widely reported, although there is evidence of some short-term negative effects on tree growth after herbicides have been used for weed control (e.g. Haywood *et al.* 2003; Jylhä and Hytönen 2006). Observations in the weeks following herbicide application in the current study indicated some pine-needle necrosis on lower branches. However, there was no evidence of negative effects on tree growth following herbicide treatments. In fact, there was some improvement in diameter growth where treatments were applied twice and where treatments were applied to the inter-rows and rows, and tree height growth was also marginally improved by herbicide treatment. Such improvements in tree growth following herbicide application are not uncommon owing to the reduced competition between the trees and understorey vegetation (e.g. George and Brennan 2002; McInnis *et al.* 2004; Wagner *et al.* 2006). The reduction in scorch height following inter-row and row herbicide treatments and prescribed burning could result in further improved growth rates in these treatments.

In order to lower the fire risk until trees reach an age at which prescribed fire can be used to reduce fuel biomass, two herbicide applications were more effective than a once-off treatment for reducing standing biomass, grass continuity, grass height and percentage grass dry weight and the density of shrubs. Rate of herbicide application was less important, but the higher rate of application was more effective than the lower rate of application in periodically reducing grass continuity and shrub density in the inter-rows and in reducing standing biomass in the tree rows. Extent of application was also less important in reducing fire risk but application in the inter-rows and rows did significantly reduce shrub density relative to the inter-row-only application and the inter-row and row treatment was important for minimising scorch height during prescribed burns. Thus, although cost savings could be made by minimising herbicide use (i.e. reducing number of applications, rate of application or extent), this would result in less effective fire risk management. Other options to reduce fuel biomass in young plantations could involve regular mechanical slashing or livestock grazing (Wilson and Collins 1979; Stephens 1998). Effects of slashing are likely to be short-lived (<one growing season) but livestock grazing could be a viable alternative, particularly where palatable grasses (e.g. *Urochloa decumbens*) are abundant in the understorey. However, this would require some development of infrastructure (e.g. fences).

There were some changes in understorey plant composition following herbicide treatments, but changes were short-lived. There was a short-term reduction in grass dry weight following herbicide treatments and a corresponding increase in the dry weight of forbs. These differences persisted for ~2 years, but by 2010, there were no differences in the relative dry weights of grasses and forbs among the different treatments. Nevertheless, the short-term decrease in grass dry weight and a subsequent increase in the abundance of non-woody forbs (e.g. *Ageratum houstonianum*, *Emilia sonchifolia*, *Lobelia purpurascens* and *Mitracarpus hirtus*) are desirable from a fire risk management perspective, as the forb component is considered less flammable than the grass component (Hogenbirk and Sarrazin-Delay 1995). To ensure persistence of these differences in plant composition, more than two herbicide applications may be required in the period up to prescribed burn age. Alternatively, the timing of treatments could be varied to ensure differences in composition persist until prescribed burning. Timing of herbicide applications is also important to ensure that differences in standing fuel biomass persist until plantations are old enough to be regularly burnt. However, herbicide treatments should be carried out >6 months before prescribed burning, because herbicide treatments do increase the flammability of the standing biomass (by reducing fuel moisture content) for some period of time (Brose and Wade 2002).

Although certain herbicide treatments were effective in reducing potential negative effects of fire, the reductions in fuel loads and the changes in fuel structure and composition observed in this study may be irrelevant in the event of a severe wildfire driven by extreme weather conditions (Bessie and Johnson 1995; Fernandes and Botelho 2004; Cruz *et al.* 2008; Cary *et al.* 2009). This is more likely to be the case where row treatments have not been applied because the row fuels can provide a linkage between the surface fuel layer and the canopy layer, resulting in the potential for crown fire propagation (Kilgore and Sando 1975; Alexander 1998; Cruz *et al.* 2006). Effectiveness of treatments in reducing wildfire hazard also diminished with time since treatment. Hence broad-scale use of herbicides to minimise potential damage to young pine stands in the event of a wildfire is currently not recommended, as further studies are needed to test the effectiveness of such treatments in reducing damage to young pine stands under a range of wildfire intensities.

Conclusion

Herbicide treatments may provide a useful tool for management of fuels before prescribed fire as certain herbicide treatments did reduce tree scorch during prescribed burning in the young pine plantations studied. Although certain treatments were effective in reducing fuel loads and altering fuel structure and composition, the effectiveness of these treatments in reducing the risk of tree damage or mortality under wildfire conditions has not been tested here.

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Appendix 1. Trends in means through time following repeated-measures ANOVA

(*a*) Standing fuel biomass in the rows, averaged across all treatments (l.s.d. = 0.97); (*b*) the row grass height interaction between time and number of applications (l.s.d. for comparisons between single and repeated applications = 10.80, and for comparisons with the control = 13.23); (*c*) the row grass discontinuity score interaction between time and herbicide treatment (mean averaged across all herbicide treatments, l.s.d. = 0.40), where higher grass discontinuity scores represent lower grass fuel continuity; (*d*) back-transformed percentage dry weight of non-grass monocots averaged across all treatments; and (*e*) back-transformed shrub density (number of shrubs over 160 m^2) in the rows averaged across all treatments. In all cases, except plot (*a*), means are covariate-adjusted.