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PROCESSES OF WOODLAND EUCALYPT REGENERATION: LESSONS FROM THE BUSH RETURNS TRIAL

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ABSTRACT: Natural regeneration may contribute significantly to eucalypt woodland management, but has uncertain outcomes. As part of a monitoring program, we sought to investigate the processes of eucalypt regeneration within the Bush Returns trial, a native vegetation management incentive scheme in the Goulburn Broken catchment of Victoria. By year 4 of the 10-year program, eucalypt seedlings were found at about 24% of sampled quadrats. This varied substantially across sites, with only half the participating properties having any seedlings. Individual trees varied widely in their seed production, but seed rain was not related to the spatial context of the trees. Seedling emergence was infrequent and seed sowing trials had very patchy, and overall low, success. Seed removal experiments indicated that seeds were removed faster and more completely in sites with more bare ground (less grass and litter) and during warmer weather. The probability of a seedling surviving summer was approximately 0.3–0.5, with some site-to-site uncertainty attributable to soil moisture availability. The processes of eucalypt recruitment are infrequent, patchy and difficult to predict. Long timeframes with appropriate incentives are needed to manage natural regeneration. Research to investigate this would require replicated experiments, with multiple treatments across multiple sites.

Keywords: Recruitment, *Eucalyptus*, woodland, restoration, seedling

BACKGROUND

Since European settlement, Australia, and rural Victoria particularly, has undergone widespread clearing of eucalypt woodlands (Yates & Hobbs 1997). The result is a landscape comprising scattered patches of remnant woodland and isolated trees girt by cropland and pasture (Lunt 1991). Restoration of eucalypt woodlands is challenging and plagued with uncertainty.

Natural regeneration, a potentially cost-effective contributor to large-scale landscape restoration (Dorrough & Moxham 2005), is limited by our current lack of understanding of how climate variability and management factors influence recruitment. Therefore investment in natural regeneration is risky (Vesk & Dorrough 2006; Dorrough et al. 2008). This risk requires managers and researchers to develop strategies for increasing native vegetation cover, based on sound ecological research (Saunders et al. 2003; Vesk & MacNally 2006). Understanding the processes of natural regeneration should assist in more effective and efficient use of resources in seeking to increase the extent and condition of native woodlands.

Bush Returns is a landscape restoration program targeting private land and designed to increase the extent and condition of native vegetation in the Goulburn Broken Catchment (Miles 2008). An open competitive tender process (conservation auction) was employed by Goulburn Broken Catchment Management Authority (GBCMA) to select landholder bids. The selection process utilized a Restoration Benefits Index comprising conservation significance multiplied by the regeneration potential divided by the landholder cost (Miles 2008). Landholders enter into a contract with the GBCMA and receive annual payments with five or ten year management plans. In most cases, the full agreement is registered on the property title for ten years. Beginning in 2005, a monitoring program commenced to assess the success of the Bush Returns scheme and the site selection criteria. Monitoring included a series of surveys of eucalypt seedlings, a network of seed-fall traps to quantify eucalypt seed production, and a series of eucalypt seedling survival experiments.

Here we report on a series of investigations into the natural regeneration of woodlands on properties where the owners receive incentives to manage their land for landscape-level increases in native vegetation through the Bush Returns trial. While much is known about the spatial pattern of eucalypt establishment across northern Victoria (Dorrough & Moxham 2005), these spatial predictors tell us where this has happened, which is not the same as where it could happen. To improve our ability to predict when and where eucalypt establishment is expected, a better understanding of process is needed. Previous modelling of the recruitment process has highlighted the sensitivity of the recruitment to the availability of seed and the survival of seedlings (Vesk & Dorrough 2006). The work we present here addresses these information needs.

The remainder of this paper is structured as follows. After a brief description of the sites a series of sections successively describes investigations of seed production and rain, the emergence of seedlings from sowing trials, seed removal by ants, and finally seedling survival. The prevalence of eucalypt recruitment is briefly discussed before presenting concluding comments.

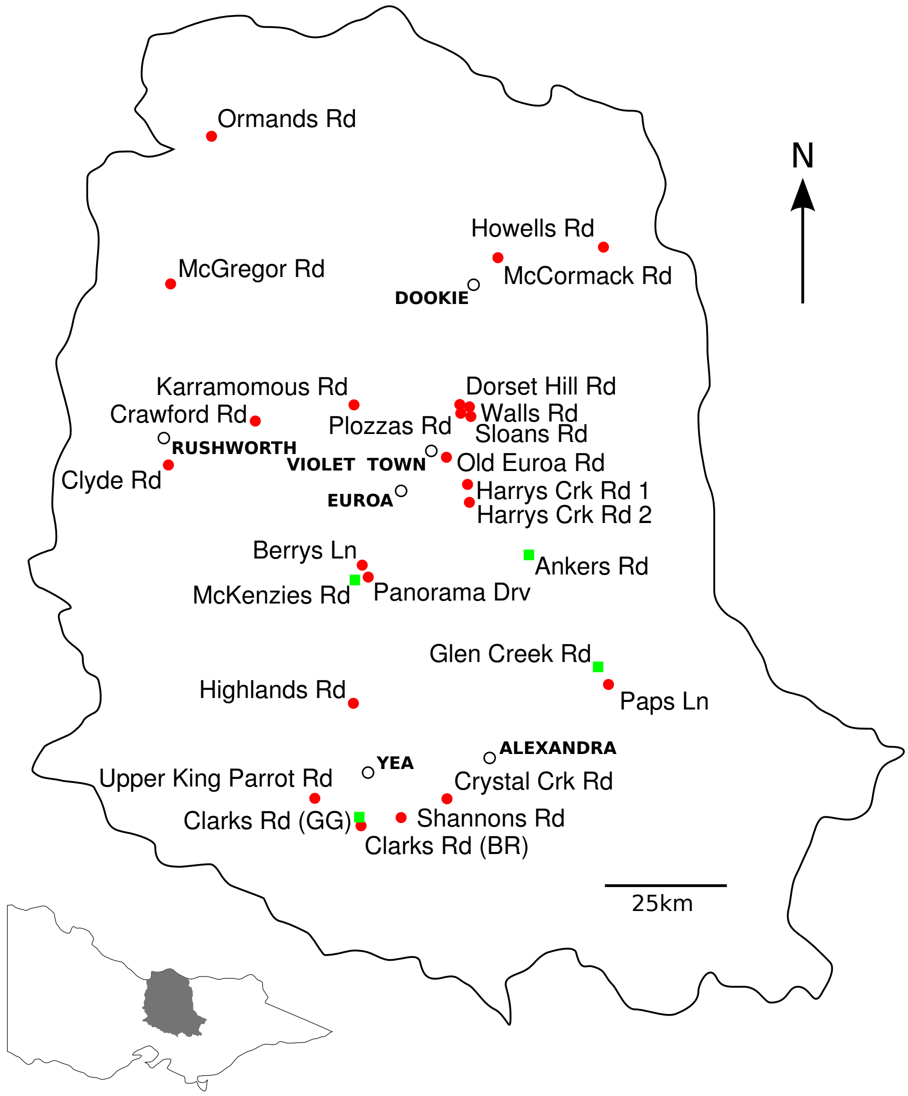

Figure 1: Bush Returns (red circles) and Green Graze (green circles) participating properties and major towns (black circles) located within the Goulburn Broken Catchment, Victoria.

STUDY SITES

In 2005 there were four properties participating in the Bush Returns incentive scheme. Fifteen properties were added in 2006, while the scheme was discontinued at one property. Four properties were added in 2007 for a total of 22 properties participating in the scheme. All properties are located within the Goulburn Broken Catchment and cover an area from Yea in the south, Rushworth in the west, and Nathalia in the north (Figure 1).

The properties span a natural rainfall gradient in three zones: Alexandra (704 mm mean annual precipitation), Euroa (648 mm) and Dookie (550 mm) (BOM 2008). The most common Ecological Vegetation Classes found at the sites are Grassy Dry Forest, Box Ironbark Forest, Grassy Woodland, Plains Grassy Woodland and Valley Grassy Forest.

The condition of the sites ranged from those with a native-dominated understorey, where light grazing had recently ceased, or had continued infrequently, to those that were more heavily grazed and where past management practices may have included cultivation, fertiliser application and sowing of exotic perennial species. Typically, the sites are relatively open and include scattered or small patches of eucalypts with a high cover ratio of native grasses to weeds. Site management plans were tailored to the needs of the site. Typical actions included changing grazing regimes through livestock exclusion for all or parts of the year, pest plant and animal control and biomass management to create open spaces for eucalypt seed contact.

SEED PRODUCTION

The summer of 2005–2006 was a strong flowering year for *Eucalyptus microcarpa* (Grey Box). In 2006, Honours student Anthony Davidson compiled a complementary dataset of seed held in the canopy of 118 individual *E. microcarpa* trees across sites, including the Bush Returns sites. The number of seed produced can be in the order of 10^6 seeds per tree, and analyses showed that local tree density and configuration influenced whole tree fecundity (Vesk et al. 2010). In that study, production was high in solitary and woodland-spaced trees and reduced under high local density. Further, solitary *E. microcarpa* produced seed that were at least as viable as trees in more contiguous configurations. Thus, solitary trees are an important feature for their own replacement and as a source for wider regeneration. As long as the trees are not too small and densely spaced, canopy cover is the primary variable determining seed production.

Many of those seeds only fall short distances from the parent tree. Seed trapping at the canopy drip-line can reveal the rates of seed fall. Conceivably seed production could be affected by tree isolation. We distributed seed traps around trees to record seed rain of *E. microcarpa* and *E. camaldulensis* (River Red Gum). This was later expanded to include *E. albens* (White Box) and *E. macrorhyncha* (Red Stringy Bark). The seed rain traps were set up at three mature tree 'isolation' levels: 'individual' (within paddock, minimum two canopy widths between trees); 'clump' (within paddock, three to nine trees with less than two canopy spaces in between, separated by at least two canopy widths from other single or grouped paddock trees); and 'linear edge' (within paddock, along a roadside or remnant edge). Eight seed traps were placed under the drip-line evenly spaced around the mature tree or clump of trees. The contents of seed traps were collected at intervals and taken back to the laboratory for assessment.

The seed traps revealed that seed rain varied through time with peaks and troughs. Troughs and peaks varied through time and after four years of collecting seed rain data, a pattern of short-term decline emerged. For all species except *E. camaldulensis* seed production per metre squared per day decreased between 2006 and 2009. This trend overlies a strong seasonal signal for these species, whereby peak seed production occurs in summer and is minimal in the cooler, wetter months. The *E. camaldulensis* trees did not follow the same pattern. *E. camaldulensis* peak seedfall occurred late 2007 but then was comparatively low for the remainder of the monitoring periods (Figure 2). Overall though, *E. camaldulensis* had the greatest maximum rate of seed production of >25 seeds m^{-2} d^{-1}. *E. macrorhyncha* had the next highest production peaking at 10 seeds m^{-2} d^{-1}, followed by *E. microcarpa*, and then *E. albens* (not shown). Contrary to our initial expectations, across species, lone, clumped and edge trees produced the same trends and there was no overall difference in production.

SEED REMOVAL

The seed that reach the ground may be predated by animals, so we studied seed removal by invertebrates (principally ants) using petri dish seed caches. This study was a continuation of an experiment conducted by Michael Longmore at two of the Round 1 Bush Returns sites in the course of his Honours research at Melbourne University. Caches of *E. microcarpa* seed were placed at six sites within these two properties. Caches were simply lidded petri dishes (9 cm diameter), with two 5 mm diameter holes on opposing sides. Seed samples used in this experiment were of local provenance and had been stored without chemical insect deterrents. Thirty caches were placed at ground level at each of the sites. Thirteen seeds were placed into each cache, each placed 2 m apart, arranged in a 6 x 5 grid. Each deployment was for five days and four nights. An Onset Hobo Pendant™ temperature logger was buried to a depth of 1 cm in the middle of each grid and logged ground temperature every 20 minutes for the duration of each deployment.

Caches were placed at two sites identified into each of three site categories: open, grassy (no tree cover, high pasture cover); open, rocky (no tree cover, low pasture cover); and treed, litter (tree cover, high litter cover). Caches were deployed in November–December 2006, February–March 2007 and April–May 2007. Each period had two deployments with a two-week interval in between.

Patterns of eucalypt seed removal by ants varied between locations and habitats (mean removal ± SE: 3.9 ± 0.9 per cache of 13 seeds); overall removal was greater at sites with tree cover than at those without (open, grassy, 2.8 ± 1.3; open, rocky, 3.3 ± 0.8; treed, litter, 5.6 ± 1.8). Seed removal was reduced in cooler months in the open, grassy sites (Figure 3). Removal appeared to increase with increasing minimum temperature rather than increasing maximum daily temperature.

The temperatures recorded at the open, rocky sites were warmer in winter than open, grassy sites, and exhibited slightly more seed removal (Figure 3). Maximum daily temperatures at both open sites in summer were very high compared to those at the treed sites. Temperatures at the treed sites appeared to be moderated from open non-shaded sites (Figure 3); during the day it was warmer in winter and cooler in summer. Seed removal was low in winter, but was much higher in summer and autumn than that at open sites.

Across all sites and categories, seed removal by ants was correlated with ground temperature ($R^2 = 0.32$), illustrating that seed removal increases with increasing temperature (Figure 3). Patterns of temperature varied between open and treed sites. On average, open sites (no tree cover) got hotter and colder than treed sites, which were somewhat buffered (Figure 3). In open sites, seed removal responded moderately to temperature, showing a slight increase in activity as the temperature increased, largely independent of groundcover (i.e. grassy or rocky). In contrast, treed sites showed a strong increase in ant removal activity with increasing temperature.

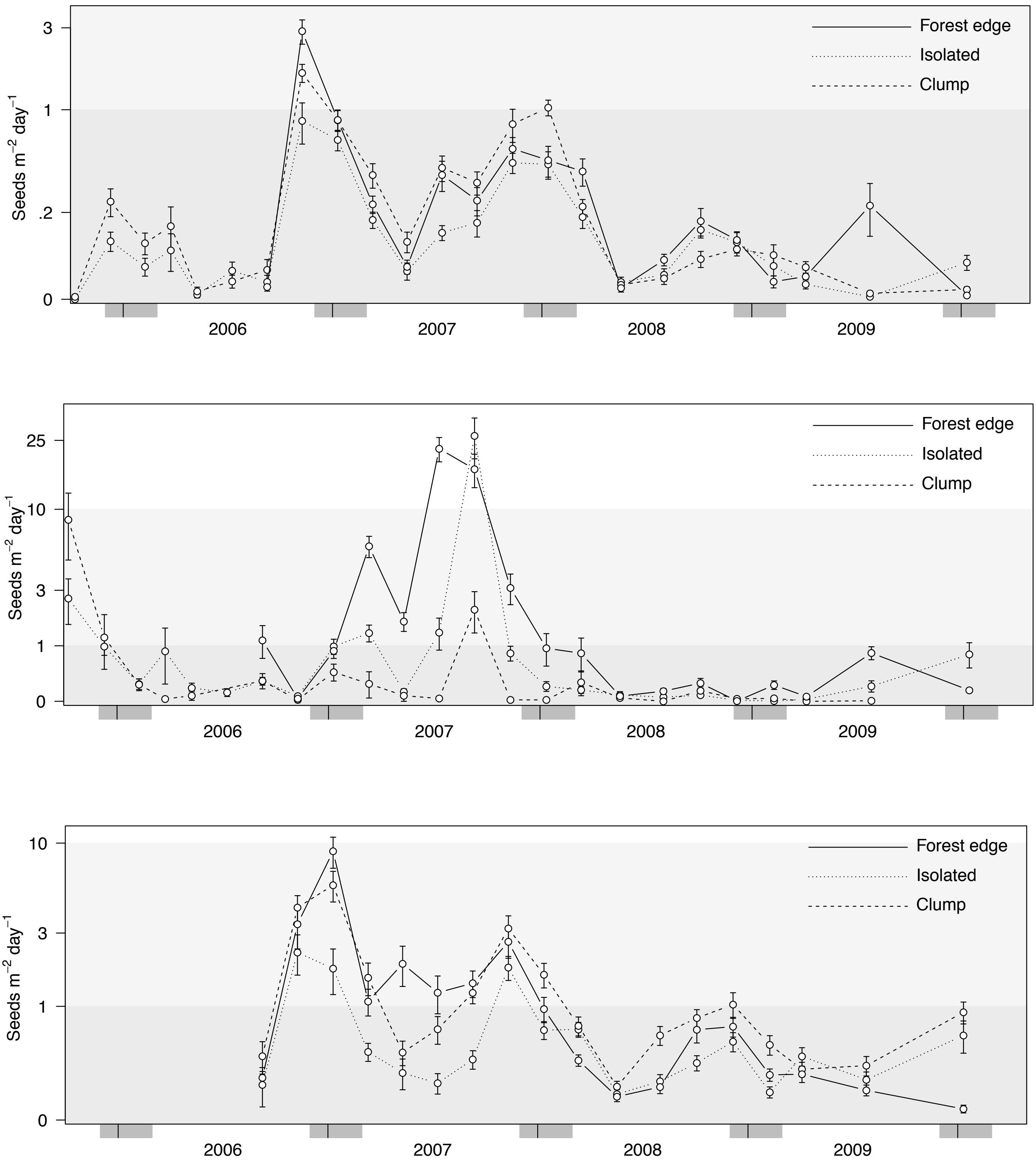

Figure 2: Average (± standard error) seed fall estimated from seed traps for three eucalypt species, from top to bottom: *E. microcarpa*; *E. camaldulensis*; *E. macrorhyncha*. Grey bars beneath axis indicate the summer months, December, January and February.

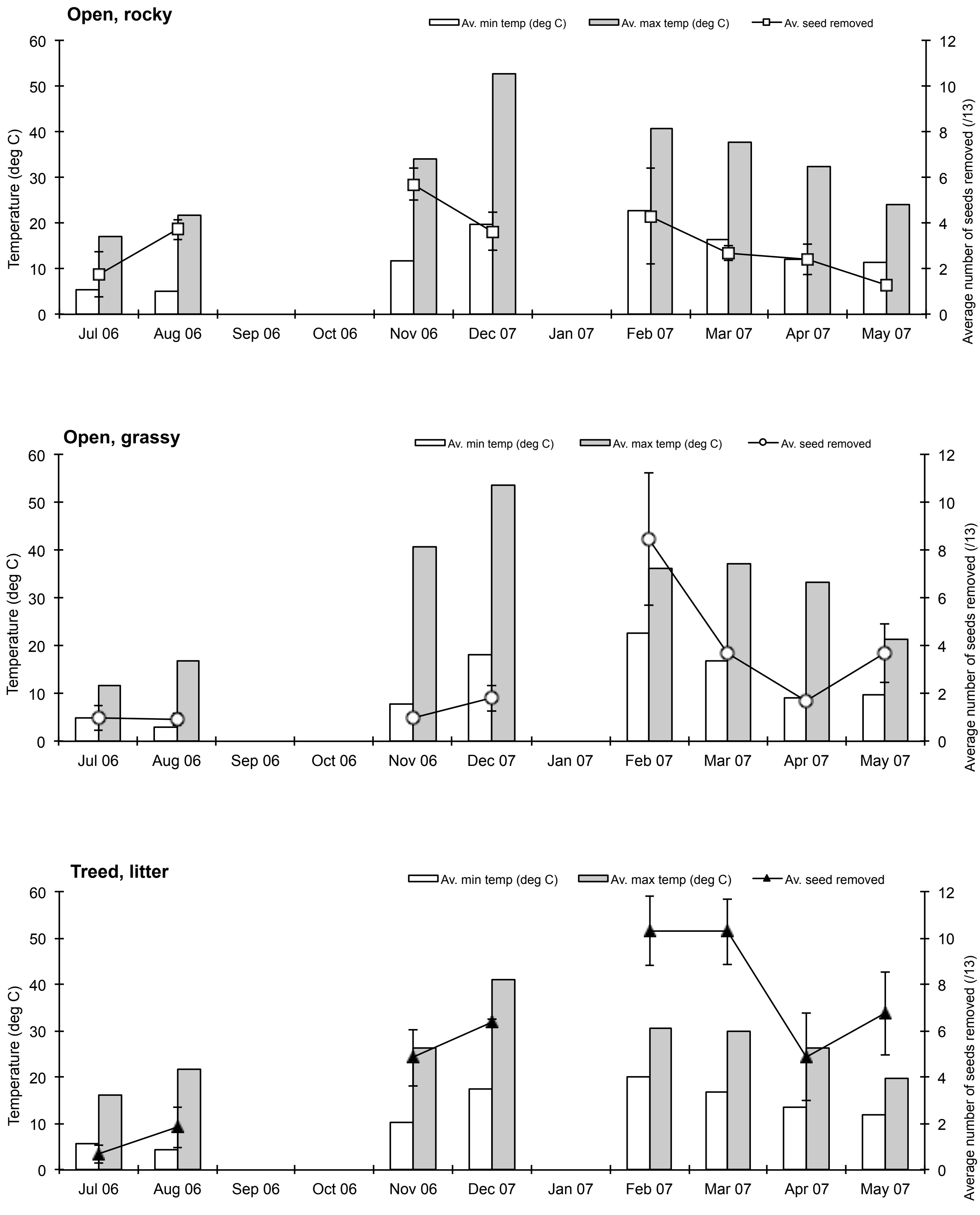

Figure 3: Ant removal of *E. microcarpa* seed from seed caches according to average daily minimum and maximum temperature (°C) at open, grassy sites, at open, rocky sites and at treed, litter sites (n = 2 each) (± 1 s.e. shown).

Removal varied according to temperature, which varied according to habitat. Ants are ectothermic, so the temperature at ground level can affect their levels of activity (Wehner et al. 1992; Cerda et al. 1998). In winter, when it was cold, removal was low at all sites. In summer and autumn, as temperatures increased, so did removal. However, there may be a limit when ground temperature becomes too high and ant activity is reduced. Temperature conditions within the treed sites were neither as hot nor as cold as those recorded at open sites in summer and autumn. The presence of trees appeared to mediate temperatures, presumably because of shading. This appeared to influence the activity of ants as more seeds were removed from caches at treed sites.

Ant species composition has been shown to differ with vegetation structure and land use in these regions (Bromham et al. 1999). It is possible that greater numbers of ants inhabit areas around trees, because this is where natural seed fall is likely to be high. This could affect the number of seeds removed in treed areas compared to areas away from trees. Complex ground covers could affect the foraging activity of ants in two ways; shading could alter ground temperature, as discussed above, and structural complexity could affect foraging efficacy (Longmore 2006; Andersen & Ashton 1985). Habitats with high litter cover (e.g. leaf litter under trees, rank grass in ungrazed pasture) make it harder for ants to locate seed because they have to forage not only around, but over and under, debris. In this context, the open, rocky habitat is most likely the simplest for ants to locate seed. However, the hotter conditions experienced at these sites in summer, and the reduced likelihood of seed being present at such sites away from trees, indicate that ant populations in these areas may have been lower to begin with.

SEEDLING EMERGENCE

Four times over 2005–2007, we attempted seed sowing trials, away from mature trees to assess germination success of artificially sown seed of *E. microcarpa* (60% viability). Various treatments were applied, but in the end no definitive analysis could be done with respect to experimental factors owing to the few germinants observed.

In 2005 seeds were spread at two seed densities: low (0.5 g/m^2) and high (2 g/m^2) (ca 25 seeds/0.1g). Plant biomass in each plot was either left intact (control), or removed at the beginning of the experiment (scalped with soil disturbance). The germination plots were caged with wire mesh and received a once-off watering at sowing. A treatment with high seed density, scalped with soil disturbance, caged and without watering was established to test the effect of not adding water to supplement rainfall. A treatment with high seed density, scalped with soil disturbance and water but no cage was set up to assess the impact of large vertebrate herbivores on eucalypt germination. Two replicates of each treatment were established at each site making a total of 48 experimental plots. Germination plots were monitored fortnightly until the end of December 2005, and bi-monthly thereafter.

Immediately after setting up the seedling emergence experiments, the Violet Town area experienced very heavy rainfall. It is quite possible that much seed was removed by runoff. There was very little evidence of germination over the whole seedling emergence experiment with only six seedlings recorded from a total of 48 experimental plots. All six seedlings were recorded at the Sloans Road property (see Figure 1), Site 1, in scalped and caged treatments. No seedlings were recorded in intact vegetation plots. Only two seedlings remained in March, with drought appearing the cause of mortality for the others.

In 2006 and 2007, 17 germination plots were established at 10 Bush Returns properties spanning gradients of rainfall, landscape position, aspect and soil type. Nine 10 x 10 cm plots were established at each of the 17 sites. These contained three replicates of three treatments: plant biomass intact, surface sown (control); plant biomass removed, surface sown; plant biomass removed, seed buried. Seed was sown at 2 g/m^2 (ca 25 seeds/0.1g). Species cover and composition at each plot was recorded at the beginning of the experiment. Each plot was monitored for recruitment of sown seed fortnightly and soil moisture was recorded at these intervals.

There were three rounds of the sowing experiment in an attempt to capture at least one period of soil moisture adequate for germination. These began on 10 May 2006, 9 August 2006 and 27 March 2007, respectively.

Seedling emergence from the 2006–2007 seed-sowing experiments was very low and variable through the three rounds of the experiment. Broadly, rounds 1 and 3 had some germinants, while round 2 had none. In total, 32 germinants were recorded in round 1 during monitoring on 23 August 2006. One new germinant was recorded two weeks later, but none thereafter for eight weeks. None of the emerging seedlings survived after four weeks. The germinants were found at four of the 17 plots: on a north slope, two crests and a flat, which were mostly at sites within the Violet Town area.

No germinants were recorded in the control (biomass intact, surface sown) plots. Scalping appeared to increase seedling emergence, as did burying seed, but owing to the low numbers, this must be interpreted with caution. No germinants were located in round 2 of the experiment (began 9 August 2006), even though it was in its second week when germinants were recorded from the first trial. In a trial beginning 27 March 2007, a total of 15 germinants was recorded across seven of the 17 sites. All but one were from scalped plots. Germination was apparently unrelated to soil moisture measurements.

Over two years, the seedling emergence experiments were largely unsuccessful, perhaps as a result of the drought. Broadly, emergence from sown seed was very low, and was restricted to the cooler months and scalped plots, indicating that ground layer inhibits emergence. A seed burial treatment was added in an attempt to control factors such as seed removal by ants (Yates et al. 1995), wind or water and to enhance seed contact with soil moisture (Clarke & Davison 2001). Although more germination was witnessed in 2006, seed burial did not enhance seedling emergence any more than did removing surface biomass. Notably, the fact that more seedlings emerged from bare plots indicates that seed predation may be less important than seedling mortality through competition for water.

SEEDLING SURVIVAL

In October 2005 two separate experiments took place in grazing exclosures (livestock-, rabbit- and kangaroo-proof) across four sites on the original three Bush Returns properties (Figure 4). Seedlings of *E. microcarpa* were transplanted into the exclosures (12 m x 12 m x 2 m). Experiment one consisted of 6 plots (+/- watering) each with 2 quadrats (+/- scalping), each with 9 seedlings. Experiment two consisted of individual seedlings planted into soil with variably sized scalped areas (0–24 cm diameter).

Figure 4: Photo of exclosure at Dorset Hill road site (see Figure 1), with transplanted seedlings and grass biomass responding to reduced grazing pressure.

In September 2007 a third seedling survival experiment was undertaken at 17 sites located across ten properties. *E. microcarpa* seedlings were planted in either intact grass (little soil disturbance) or into scalped patches (28 cm diameter vegetation removed) and protected with plastic mesh tree-guards (exclosures were not erected). Sites comprised a number of locale types: north-facing slopes, south-facing slopes, higher flat areas, and lower flat areas. Some 35 seedlings were planted at each site (15 intact, 20 scalped). Seedlings were purchased from a local indigenous nursery and were approximately six months old. Immediately after planting, all seedlings were watered. This was repeated two weeks later, after which the seedlings were not watered again. Seedling survival was monitored until April 2009.

In the first study period (the four exclosures), we found that scalping increased seedling survival by at least four-fold (Figure 5). We also found that watering had little effect in scalped plots, while it increased seedling survival two-fold in intact plots. Two further summers in the field indicated that survival through the first summer is critical and that mortality through subsequent summers is reduced, though may still be high at harsh sites. Between-site variability in the survival of planted seedlings was more or less maintained throughout the second summer of the experiment (2007–2008). Experiment two (by Honours student Alexandra Thorp) revealed that gap size did influence seedling survival, but that gaps had to be >20 cm radius to reduce mortality; these were rare in the paddocks. Although seedlings in Experiment three were potentially exposed to greater grazing pressure than those of Experiments one and two, being in tree guards only, we have no evidence that survival was any different between the experiments. During the third experiment in 2007, median summer survivorship was 0.37 [0.09, 0.64]. Estimated survivorship was uncertain and varied widely among locations. Broadly, mortality was greater in the north of the catchment, on ridges and north-facing slopes. A statistical model of mortality revealed that seedling mortality was higher at sites experiencing higher maximum temperatures and that were likely to shed water rather than accumulate it, due to their position in the landscape (Morris et al. 2013). Comparing models built for each experiment showed that overall probability of surviving summer was approximately 30% to 50%. Site-to-site variation contributed the most to model uncertainty. Experiment three had the least parameter uncertainty, because it involved four times as many sites as the previous two.

SEEDLING OCCURRENCE

Between 2006 and 2008, 460 quadrats, 15 m x 15 m, were surveyed for seedlings and saplings across the 22 Bush Returns properties. Small seedlings (<50 cm) were relatively infrequent in all surveys and where they occurred, larger seedlings were also present. The size range could result from either or both of, different-sized seedlings of

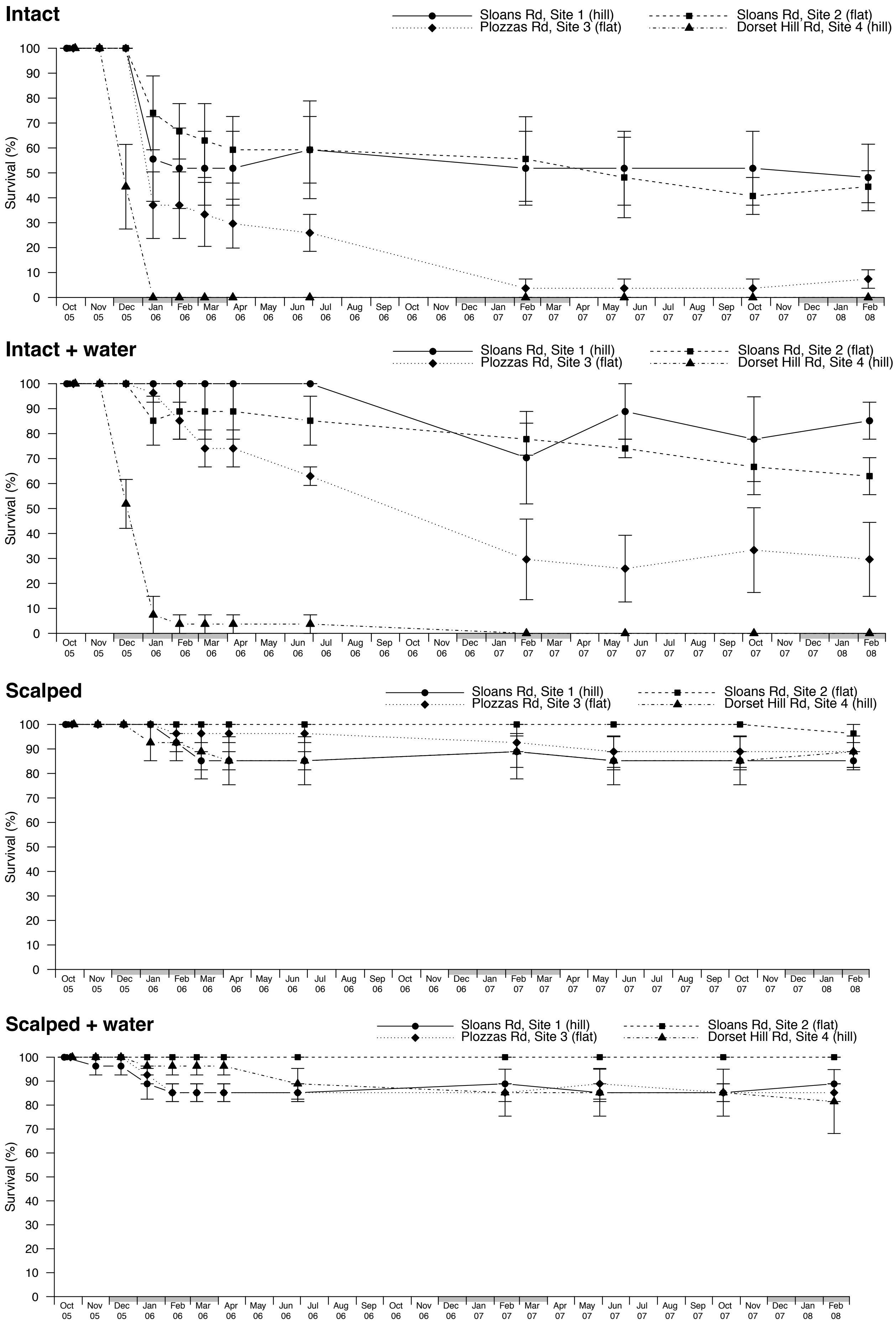

Figure 5: Seedling survival over three years in experimental exclosures, under water and scalping treatments with 3 replicates of 9 seedlings.

one cohort, or multiple distinct cohorts of similarly-sized seedlings. The seedlings are likely to have been recruited before the agreements, but are nonetheless 'captured' by Bush Returns. Hence, we analysed a wider size range to increase statistical power. Eucalypt seedlings (<2 m tall) were observed in 111 quadrats (from a total of 460), about 24%.

Seedlings were more common closer to trees (essentially absent beyond 60 m from tree trunks), where cover of moss and lichen and bare ground were greater and they received little winter sun (south-facing slopes and southern locations). A model based on these data showed that moss and lichen cover were positively correlated with greater densities of seedlings. Seedling density predictions were improved when including the effect of measured remotely-sensed soil potassium (K). Our understanding of this is that heavier soils have higher K content and fewer seedlings (Vesk et al. 2010).

Using those models of seedling distribution we estimated the number of seedlings expected at 30 m from trees at each of the sites, holding all environmental co-variates at their mean. That enabled comparison of the sites 'all else being equal'. We then ranked the sites on that expected seedling density. We found that this ranking was positively correlated with the Restoration Benefits Index ranking employed by GBCMA in their assessment of landholder proposals ($r^2 = 0.24$, $n = 22$). This lends validation to the assessment employed by GBCMA, but we note the relationship is not perfect and it represents seedlings present very early in the landholder agreements.

WHAT HAVE WE LEARNED?

Seed fall is quite variable between years, although it should be reliable around large trees. Seed that hit the ground may be preyed on by ants and other animals. Seedling emergence results suggest, however, that freedom from mortality due to soil moisture deficit is a major determinant. Good autumn rains need to follow strong seed rain years. And there need to be gaps in which seedlings can establish. Then summer rains are needed for good seedling survival.

Some sites, those exposed to higher soil moisture deficit, are systematically greater mortality risks for seedlings. For managers, this suggests that some sites, those with light soils and greater moisture availability, may be the best choices. Complementarily, if sites that are high risk but desired, then more time and extra effort may be required for eucalypt seedling recruitment.

Despite our earlier expectations, over the years studied here (which coincided with the millennium drought), seed fall showed no obvious pattern associated with tree context. We did not observe a difference in seed fall from nearby trees that were isolated, clumped or on the edge of a forest block.

Multiple experiments have provided greater certainty about our estimate of overall *E. microcarpa* (Grey Box) seedling survival, and factors affecting survival. These factors include weather, topographic position and competition from grass. Despite the third experiment, which more than doubled the number of properties included, site-to-site variation still dominates the model's parameter uncertainty. With the sample size used, estimating survival beyond the first year is problematic, particularly at sites with high mortality where the sample size becomes very small or even zero following the first summer. While we suspect that survival is high (>80%), based on sites where enough seedlings remain after a single summer, it is unwise to extrapolate to harsher sites where survival through the first summer was very low.

For these reasons we recommend a monitoring program of some larger scale revegetation efforts within the catchment. This would require accurate recording of the identity and quantity of plants going into the ground and then a program of monitoring that could track their survival either as individuals (or subset of) or as cohorts. This should be accompanied by data on site characteristics such as soils, topographic position, rainfall and grazing.

We noted enhanced grass growth inside exclosures, which indicates substantial grazing pressure by marsupial and rabbits at some sites. This has at least two implications. First, the persistent grazing pressure will limit the response of sites, even when livestock grazing is excluded. Second, if this limitation is severe, this might suggest that some means of reducing overall grazing pressure is needed.

All processes that we have addressed here operate over long time scales and thus future monitoring is important. These studies were conducted during the millennium drought, likely affecting the seed rain, germination and seedling survival. By building models from empirical data one can determine what parts of the landscape have greater regeneration potential. For example, eucalypt recruitment is more often found at sites with trees to provide seed, less irradiance in winter (southern end of catchment and south-facing slopes) and lighter soils. When followed up with on-ground assessment we can determine better how good a site is in terms of regeneration potential relative to others with similar environmental conditions. Continuing the example, if site assessment found relatively high moss, lichen and bare ground, then the site would have high potential for regeneration. Model predictions can also be used to monitor change on existing sites. By monitoring sites through time, trajectories of change can be modelled and the performance of any site can be compared with the predictions.

We do not claim to have evaluated effectively the Bush Returns program because this concerns only the first part of the landholder agreements. We still know little about the effectiveness of specific management actions to increase extent and quality of native vegetation. To fulfil the GBCMA's desire to learn about a range of different management actions, such as grazing, burning or applying herbicide to reduce biomass competition, or soil disturbance, then a dedicated, replicated experiment would be needed. Given the substantial spatial variation of the regeneration processes we have studied, the trial would have to occur on a large fraction (>10) of the Bush Returns sites, with replicates (2–5) at each of these. In an adaptive management approach to vegetation management (Rumpff et al. 2011), one can model outcomes of management from best available knowledge but ultimately these models need to be updated with data. Informative data will come from a structured approach to allocating management (i.e. experiments).

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