South African Journal of Botany 90 (2014) 109–113

Contents lists available at ScienceDirect

South African Journal of Botany

journal homepage: www.elsevier.com/locate/sajb

Short communication

Is broad-scale smoke–water application always a useful tool for improving seedling emergence in post-mining restoration? Evidence from jarrah forest restoration in Western Australia

Matthew I. Daws [a,*], Katherine S. Downes [b], John M. Koch [a], David Willyams [a]

[a] Environmental Research Department, Alcoa of Australia Ltd., Huntly Mine, P.O. Box 172, Pinjarra, WA 6208, Australia
[b] School of Agriculture and Environment, Curtin University, P.O. Box U1987, Perth, WA 6845, Australia

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form 24 October 2013
Accepted 30 October 2013
Available online 3 December 2013

Edited by J Van Staden

Keywords:
Germination
Mine rehabilitation
Seed
Smoke–water

ABSTRACT

It has been widely advocated that smoke–water application to topsoil can substantially improve restoration success by enhancing seed germination. This is despite few studies having tested the effects of smoke–water on seedling emergence in field-scale restoration trials. Here we report the effects of applying a commercially available smoke solution (Regen 2000®), at rates between 0 and 100 mL m^{-2}, on jarrah forest sites being restored after bauxite mining in the southwest of Western Australia. Smoke solutions stimulated the seed germination of a range of species in laboratory experiments. In addition, smoke–water stimulated germination of *Stylidium affine* seeds sown directly into the first field experiment. However, apart from the effect on sown *S. affine* seeds, smoke–water application had no effect on subsequent seedling numbers, species richness or the relative proportion of seedlings in different growth-form categories in either of the two field experiments. These findings suggest that smoke–water application does not always ensure enhanced restoration outcomes.

1. Introduction

In the absence of other fire-related cues, smoke produced by burning plant material has been shown to stimulate germination of a broad range of species from both fire-prone (Roche et al., 1997; Keeley and Fotheringham, 1998; Brown et al., 2003; Måren et al., 2010) and non-fire prone environments (Drewes et al., 1995; Pierce et al., 1995; Doherty and Cohn, 2000; Adkins and Peters, 2001; Daws et al., 2007). As a result, the use of smoke as a field-scale technique for stimulating germination of desirable (e.g. native species in restoration projects) and undesirable (e.g. weeds) species has been proposed on a number of occasions (Light and Van Staden, 2004; Daws et al., 2007; Stevens et al., 2007; Light et al., 2009). However, few studies have tested the utility of smoke as a tool for stimulating germination in large-scale restoration projects.

Smoke technology has found applications in restoration projects with examples of smoke application to: (1) comparatively undisturbed native topsoil seedbanks, (2) topsoil returned in restoration operations, and (3) seeds prior to their use in broad-scale seeding (Rokich and Dixon, 2007). When applied to minimally disturbed *Banksia* woodland and jarrah forest soils in the southwest of Western Australia, aerosol smoke application resulted in very significant increases in the number of emergent seedlings (Roche et al., 1997, 1998). Aerosol smoke application is generally more effective at stimulating seedling emergence from soil seed banks than liquid smoke (Rokich and Dixon, 2007). However, applying aerosol smoke is both logistically challenging as a broad-scale technique and potentially limited in some locations by restrictions on the use of fire. Therefore, for smoke to be used on a broad-scale, the application of liquid smoke is likely to be the most practical approach (Rokich and Dixon, 2007) and was consequently used in the field experiments we report here.

The jarrah forest has multiple species that respond to smoke application either in *ex situ* germination tests or in a field setting (Roche et al., 1997; Norman et al., 2006b). Here we report the results of two field experiments in the jarrah forest where smoke solution was applied to jarrah forest sites to be restored after bauxite mining. We also tested whether smoke has a differential effect on emergence of different plant growth-forms since this has been reported previously based on laboratory germination tests (Brown et al., 2003). Smoke–water has been previously applied to jarrah forest restoration (Roche et al., 1997). However, the experiments we report in this study had the advantage of using multiple smoke concentrations, and one experiment included a known smoke responsive species (*Stylidium affine*) as a

* Corresponding author.
E-mail address: matthew.daws@alcoa.com.au (M.I. Daws).

0254-6299/$ – see front matter © 2013 SAAB. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sajb.2013.10.015

positive control. Including this species in the trial provided confirmation of both the germination stimulating activity of the smoke solution used, and that appropriate smoke–water concentrations were used.

2. Methods

2.1. Site description

Experiments were established at Alcoa of Australia's bauxite mining operations in the jarrah forest of Western Australia (32°35′06′′ S, 116°06′44′′ E), ca. 100–180 km south of Perth. The region has a Mediterranean-type climate with cool, wet winters and hot, dry summers. Average annual rainfall is ~1200 mm. The average summer monthly maximum temperature is ~28 °C and the average winter minimum is ~5 °C. The overstorey vegetation within the mining envelopes is generally dominated by jarrah (*Eucalyptus marginata*) with varying densities of marri (*Corymbia calophylla*). In addition, there is a small-tree component, with *Banksia grandis*, *Allocasuarina fraseriana*, *Persoonia longifolia* and *Xylomelum occidentale* being the most common species. The undergrowth consists of sclerophyllous shrubs (to 3 m tall) and herbs predominantly in the Myrtaceae, Proteaceae, Fabaceae, Restionaceae, Orchidaceae, Apiaceae, Liliaceae (*sensu lato*), Ericaceae, Asteraceae and Cyperaceae.

Mine pits range in size from 1 to 20 ha and are surrounded by unmined forest. The rehabilitation process has the objective of establishing a self-sustaining jarrah-forest ecosystem. Rehabilitation involves reshaping the mine pit, returning topsoil and deep ripping to alleviate compaction. The returned topsoil is usually sourced from recently cleared forest areas that have yet to be mined. After re-spreading and ripping, this topsoil contains ~ 110 seeds m^{-2} (Koch et al., 1996).

2.2. Field experimental design

In March 1997, four 1 m × 1 m plots were established within each of seven newly rehabilitated (i.e. after landscaping, topsoil return and contour ripping) mine pits. In the centre of each 1 m × 1 m plot, 200 *Stylidium affine* seeds were sown and covered with topsoil to a depth of 5 mm. Each of the four plots was randomly allocated either 0, 10, 50 or 100 mL m^{-2} of a commercially available liquid smoke treatment (Regen 2000®, Tecnica Pty. Ltd., Bayswater, Victoria, Australia). All solutions were made up to 100 mL m^{-2} with water and applied with a backpack sprayer. Plots were monitored in October 1997 and all seedlings present, identified and recorded.

In March 1998, a second field experiment of four 20 m × 20 m plots was established within each of six replicate mine pits. Within each pit, the four plots were randomly allocated in the following smoke treatments: 0, 10, 50 or 100 mL m^{-2} of Regen 2000®. All treatments were made up to 100 mL m^{-2} with water. The smoke treatments were applied to the 20 m × 20 m plots using a backpack sprayer. A 4 m × 4 m monitoring plot was established in each of the four corners and the centre of each 20 m × 20 m plot. This resulted in a sampling area of 80 m^2 per 20 m × 20 m plot. Between 25 October and 9 November 1998, all seedlings within the 4 m × 4 m plots were identified and counted.

2.3. Ex situ seed germination tests

A smoke treatment was applied to seeds of four jarrah forest species (*Conostylis aculeata*, *Grevillea wilsonii*, *Hyalosperma cotula* and *Stylidium hispidum*) to test the efficacy of the smoke solution used in the field experiments. Smoke treatments consisted of 10%, 25% and 50% concentrations of Regen 2000®, and a de-ionised water control. Three replicates of 50 seeds per species were soaked in 10 mL of each treatment for 24 h. Seeds were then sown into a punnet of potting mix in a greenhouse at Alcoa's Marrinup nursery which is within 15 km of the sites used for the field experiments. No heating was supplied and irrigation was automatic mist watering. Monitoring for seedling emergence occurred weekly for 10 weeks (after which very limited emergence occurred).

2.4. Statistical analysis

General linear models implemented in Minitab 16 (Minitab Inc., State College, PA, US) were used to assess effects of smoke application rate on species richness (1997 and 1998 trials), seedling density (1997 and 1998 trials) and emergence of *Stylidium affine* (1997 trial). To account for variability across mine pits, 'pit' was included as a random variable. To ensure normality, seedling density was $\ln(n + 1)$ transformed and *S. affine* emergence arcsine transformed.

For the 1998 field trial, seedlings were categorised into one of several growth form/plant-type categories to assess whether smoke application had a differential effect on emergence of plants in different growth-form categories. Plants were categorised as either: (1) ephemerals (short-lived native species), (2) introduced weeds, (3) re-seeders or (4) re-sprouters. Two fire-response syndromes can be described for species in the jarrah forest. Re-sprouters survive fires as individuals. Re-seeders are killed by fire and must re-establish through germination and seedling establishment (Bell, 2001). Species were classified as re-sprouters and re-seeders based on the literature (Bellairs and Bell, 1990; Bell et al., 1993; Ward et al., 1997; Smith et al., 2000; Norman et al., 2006a; Burrows et al., 2008). Non-native species and native ephemeral species were classified according to the FloraBase database (Western Australian Herbarium, 2012). Ephemerals and weeds are also considered to be re-seeders, although, for the purposes of this study, the re-seeder category used consisted of the longer-lived species.

To test for differences in germination response to the different smoke–water concentrations, one-way ANOVA followed by Fisher's *post hoc* tests was applied to each of the four study species from the *ex situ* germination tests. Germination percentages were arcsine transformed prior to analyses.

3. Results

3.1. Field experiment 1 (1997)

A total of 1,402 seedlings representing 47 species were recorded across the seven rehabilitated mine pits. Compared with the control treatment, no concentration of applied smoke–water had either a positive or negative effect on the number of emergent seedlings (GLM, $F_{3,18} = 0.56$, $P = 0.647$; Table 1) or on the species richness of the seedling community (GLM, $F_{3,18} = 0.61$, $P = 0.618$; Table 1). However, smoke–water application at each of the three concentrations enhanced emergence of seeds of *S. affine* that had been sown into the plots. There was a significant effect of smoke–water application on *S. affine* emergence (GLM, $F_{3,18} = 41.62$, $P < 0.001$; Table 1) with smoke application rate acting in a dose dependent manner: emergence was greatest (41.4%) at the highest smoke concentration (100 mL m^{-2}).

3.2. Field experiment 2 (1998)

A total of 32,231 seedlings representing 210 species were recorded across the six rehabilitated mine pits. There was no effect of smoke treatment on either the total number of seedlings (GLM, $F_{3,15} = 1.24$, $P = 0.33$; Table 1) or species richness (GLM, $F_{3,15} = 0.77$, $P = 0.529$; Table 1). In addition, there was no effect of smoke treatment on the pattern of seedling distribution across the four growth-forms analysed (MANOVA Pillai's $\lambda = 0.454$, $P = 0.809$; Fig. 1).

3.3. Ex situ seed germination tests

In the germination trial, at least one concentration of smoke–water significantly enhanced seed germination for two (*Grevillea wilsonii* and *Stylidium hispidum*) of the four species (Fig. 2). For three species,