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Recovery of Pindan vegetation on seismic lines

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Abstract. Exploration for oil and gas resources requiring the clearing of seismic lines has been occurring in central and northern Australia for many years. For example, seismic surveys have been conducted in the West Kimberley region of Western Australia since the 1960s. Despite this being a widespread practice, the recovery of vegetation on seismic lines has not been well studied. To better understand vegetation recovery in the West Kimberley, we conducted vegetation surveys on recovering seismic lines cleared using a raised-blade technique, from ~two months to 4.9 years post-clearing, and compared them to paired control plots. Generally, the vegetation structure and community composition on seismic lines recovered quickly, with no discernible difference between control and seismic plots that were cleared more than 6 months prior. Some individual vegetation characteristics (e.g. understorey density and overstorey cover) recovered slowly, whereas other characteristics such as the number of individual grasses, recovered quickly. Vegetation recovery was confounded by the time since fire, which accounted for differences in vegetation structure at 1–2 years and 3–4 years since clearing. The fast recovery rate observed suggests that raised-blade clearing may not present a lasting impact on Pindan vegetation in the West Kimberley.

Additional keywords: disturbance, fire, recovery, seismic line.

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Introduction

Seismic surveys are a common technique used in onshore oil and gas exploration around the globe, involving the clearing of tracks to allow access for seismic equipment. These survey lines are often created in a grid pattern, and only used by vehicles for a few months before being left to passively recover. Seismic surveys are common across northern and central Australia, and have occurred in the West Kimberley region of Western Australia since the 1960s (Klepacki *et al.* 1985), and more frequently after the discovery of oil at Blina Station in 1981 (Taylor 1992); however, their recovery has received little scientific attention. In fact, only two examples of targeted research were identified from anywhere in Australia: Klepacki *et al.* (1985), which is a state government technical report, and O'Loughlin (1989), which was published in a gas industry magazine. The majority of studies examining the recovery of vegetation on seismic lines are from regions with vastly different climates and vegetation types, such as North and South America (Fiori and Zalba 2003; Lee and Boutin 2006; van Rensen *et al.* 2015). These areas generally experience cold winters with snowfall and forests of tall trees (Lee and Boutin 2006), whereas northern Australia is much warmer with vegetation types ranging from arid hummock grasslands to tropical rainforest. As such, results from these studies cannot readily be interpreted to inform potential impacts associated with seismic surveys in an Australian context.

Historically, clearing of seismic lines involved removing topsoil, which can result in significant water and wind erosion, especially in arid Australian ecosystems, with little recovery occurring for decades after (O'Loughlin 1989). In contrast, contemporary seismic techniques use raised-blade clearing, where vegetation is pushed from the soil surface, thereby minimising disturbance to the topsoil and seed bank, and encouraging more rapid and efficient rehabilitation (O'Loughlin 1989). As a result, vegetation on seismic lines cleared using the raised-blade technique can recover within a few years, depending on the vegetation type, wind and water erosion, and use by animals or vehicles (Klepacki *et al.* 1985).

The most widespread land use in the West Kimberley is pastoralism, and the average size of a cattle station in the region is 230 406 ha (https://agric.wa.gov.au/n/4885). Cattle are typically grazed on native vegetation, with some introduced species, which is seldom cleared for pasture improvement or cropping. Across much of the West Kimberley, fence lines, station tracks, and seismic lines are the only 'infrastructure' present. The disturbance footprint of seismic clearing is of lower intensity than land cleared for cropping, but the presence of tracks can have more nuanced effects, such as fragmentation (Reed *et al.* 1996; Goosem 2007), and flow-on effects on animal behaviour (Dawson *et al.* 2018). Cattle often use seismic lines for movement (Klepacki *et al.* 1985; Dawson *et al.* 2018), potentially inhibiting recovery. In the present study, we investigated the recovery of seismic lines in the West Kimberley. We monitored the vegetation recovery on seismic lines from ~two months to 4.9 years post-clearing, to identify structural and community changes during recovery.

Methods

The West Kimberley is within the Dampierland Bioregion (Thackway and Cresswell 1995), that covers more than 80 000 km^2 of north-west Western Australia (Bastin and the ACRIS Management Committee 2008). The region experiences a tropical, monsoonal climate, with highly variable summer rainfall (November to April). Broome Station (65 km west of the closest study site) has an average rainfall of 781 $\pm$ 300 (s.d.) mm (Bureau of Meteorology 2019). Although there are weather stations closer to the study site, all had incomplete data for the period of the survey, so were not used. Expected rainfall for the period between clearing and each survey was calculated using the sum of the monthly averages for the appropriate time period, and the actual recorded rainfall within this time was generally within 10% of the expected total (Table 1).

The Pindan vegetation type is widespread in the region, constituting a 'grassland wooded with a sparse upper layer composed of mainly eucalypts with a dense, often thicket-forming, middle layer predominantly of wattles' (Kenneally *et al.* 1996; p. 32). Fires (both human caused and naturally occurring) are common and widespread throughout the West Kimberley, both historically and currently (Russell-Smith *et al.* 2003), and the vegetation recovers from fire quickly (4–5 years) (Radford and Fairman 2015).

This study was part of a larger project investigating the disturbance ecology of the greater bilby (*Macrotis lagotis*), resulting in sites being selected to represent appropriate bilby habitat: generally, patches of grassland/open woodland with scattered tall shrubs and trees, on a red sandy substrate. Six study sites were selected across four previous seismic surveys, Yulleroo, Yulleroo West, and Yulleroo North (all cleared in July 2011), Jackaroo (cleared in September 2014), Yakka Munga 3D (cleared in September 2015) and Yakka Munga 2D (cleared in August 2012) (Fig. 1; Table 1). A 2D seismic survey involves clearing a few long lines across a large area (often over 10 km), giving low resolution data regarding the underlying resource. A 3D survey generally comes after a 2D survey, and involves clearing a 200 m $\times$ 200 m grid pattern of seismic lines across the same area, giving higher resolution data. All seismic clearing for this study was conducted using a raised-blade technique. All sites were on active pastoral stations, with cattle present throughout, at stocking rates typical of the region (~3–5 head/km^2).

Table 1. The dates of clearing at each site, and of multiple surveys conducted at each site, showing the appropriate age categories

The total rainfall recorded between the clearing and the survey, with the average rainfall (Bureau of Meteorology 2019) for that same period, and the percentage difference, are shown. Time since clearing is shown in days (d), as used in linear mixed-effects modelling, and years (y) or months (mo), when binned for multivariate analysis

			Rainfall in the since clearing						
	Date of clearing	Date of survey	Rainfall since clearing (mm)[A]	Average rainfall in time since clearing (mm)[A]	% Difference	No. of plot pairs	Time since clearing	Time since clearing binned	Date of most recent fire (and number of fires between clearing and survey)
Yulleroo	July 2011	Nov 2015	2751	2510	9.6	1	1587 d	4–5 y	5/09/2015 (3)
		Jun 2016	3089	3123	−1.1	1	1806 d	4–5 y	5/09/2015 (3)
Yulleroo North	July 2011	Nov 2015	2751	2510	9.6	1	1586 d	4–5 y	1/05/2015 (4)
		Jun 2016	3089	3123	−1.1	1	1806 d	4–5 y	1/05/2015 (4)
Yulleroo West	July 2011	Jul 2015	2750	2498	10.1	4	1467 d	4–5 y	1/09/2014 (2)
		Nov 2015	2751	2510	9.6	4	1586 d	4–5 y	5/09/2015 (3)
		Jun 2016	3089	3123	−1.1	4	1804 d	4–5 y	5/09/2015 (3)
Yakka-Munga 3D	Sept. 2015	Oct 2015	0	1	–	9	50 d	<6 mo	Varied (0)
		Jun 2016	339	614	−44.9	9	265 d	6–12 mo	Varied (0)
Yakka Munga 2D	Aug. 2012	Oct 2015	2094	1877	11.6	4	1183 d	3–4 y	Varied (0–1)
		Jun 2016	2433	2491	−2.3	4	1400 d	3–4 y	Varied (0–1)
Jackaroo	Sept. 2014	Nov 2015	468	627	−25.5	4	419 d	1–2 y	1/5/2015 (1)
		Jun 2016	807	1240	−35.0	4	637 d	1–2 y	1/5/2015 (1)

[A]Broome Airport Weather Station (BOM station 3003) is 65 km west of the nearest study site. Records are complete since 1939.

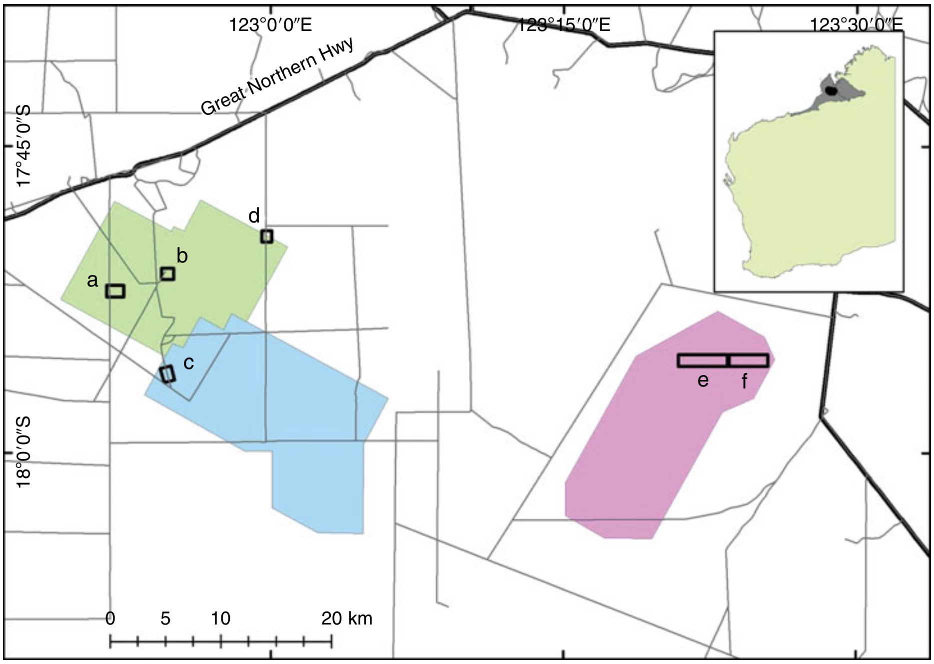

Fig. 1. The six sites included in the current study, sampling across four seismic surveys Both the Yakka Munga 2D and 3D seismic surveys are included within the one polygon (red), as the 2D survey involved clearing a few lines within the same extent. Each black box represents a site. The Yulleroo 3D seismic survey (blue polygon), contains Yulleroo West (*a*), Yulleroo (*b*) and Yulleroo North (*c*). The Jackaroo 3D seismic survey (black polygon) contains Jackaroo (*d*). The Dampier land Bioregion is shown in grey in the inset.

Vegetation surveys were conducted in 2015 and 2016 (Fig. 1). As the time line of the current study did not permit monitoring of seismic lines from creation through to complete recovery, seismic lines of different ages were used, with each study site revisited at least once.

Vegetation surveys

At each site, multiple paired plots (1–9 pairs) were surveyed (Table 1). Each plot-pair consisted of two 4 m × 10 m vegetation plots; one located on a seismic line (seismic), the other located adjacent (50 m away) in the undisturbed vegetation (control). The unbalanced design was due to logistical and timing constraints during fieldwork. Twenty three plot pairs were surveyed at least twice, ranging from 50 days to 4.9 years post clearing, providing a total sample of 50 control plots and 50 seismic plots (Table 1). Only plot pairs at Yulleroo West were surveyed three times.

Vegetation plots were 4 m wide (to account for the full width of the seismic line) and 10 m long. As seismic lines are a discrete disturbance (vehicles do not leave the track), we considered the seismic and control plots to be independent. At each plot, a range of vegetation parameters were recorded. The time since clearing was calculated from records provided by Buru Energy, and binned into five categories (<6 months, 6–12 months, 1–2 years, 3–4 years, and 4–5 years). Time since fire was calculated from fire scar data from the Northern Australian Fire Information (NAFI) website (www.firenorth.org.au, accessed 10 October 2019). Of the 100 total survey plots, 56 had burnt since being cleared, and some had burnt four times (Table 1).

A visual estimate of understorey cover (%) was made by the same person at each plot, indicating the proportion of the plot with understorey, as opposed to bare ground. The estimated average understorey height (cm) was recorded, using a 1 m touch pole for comparison. Understorey density (the ‘thickness’ of the grassy layer) was recorded using a touch pole, positioned vertically on 20 randomly-placed points within the plot, and recording the number of vegetation ‘touches’ at three height categories. Although 20 points is relatively few in a 40 m^2 plot (e.g. see McGregor *et al.* 2014), understorey cover visual estimate (%) was significantly correlated with touch pole intercepts at 0–10 cm ($P < 0.001$, $R^2 = 0.52$), 10–30 cm ($P < 0.001$, $R^2 = 0.52$), and 30–100 cm ($P < 0.001$, $R^2 = 0.73$). A visual estimate of overstorey cover (% estimate) was also recorded across the plot (i.e. the percentage of the plot in shade). The number of individual tufts of grass, shrubs, trees <3 m, and trees >3 m in each plot were counted. All plant species present in each plot were collected for identification by an experienced botanist (Andrew A. Mitchell), and species richness calculated as the number of species present.

Statistical analysis

Two approaches were used to investigate vegetation recovery: multivariate analysis of vegetation structure and community composition in PAST ver. 3.11 (Hammer *et al.* 2001), and analysis of the response of individual vegetation characteristics to clearing, using linear mixed-effects models in R (ver. 3.3.2) (R Core Team 2018). Vegetation structure included only the quantitative variables measured at each plot, and the community composition included the presence or absence of all species recorded. Given each 'time since clearing' category was represented by a spatially autocorrelated set of vegetation plots, the confounding effect of site was accounted for in each analysis approach, outlined below. First, the vegetation structure (all vegetation characteristics considered together) was compared between seismic and control plots using an analysis of similarity (ANOSIM) using a Euclidean distance similarity index. To normalise data recorded on different scales, all vegetation characteristics were scaled by subtracting the mean and dividing by the standard deviation. Second, the vegetation characteristics that accounted for dissimilarity were identified using a similarity percentage analysis (SIMPER). Community composition (the presence or absence of each plant species) was compared between seismic and control plots using an ANOSIM with a Bray–Curtis similarity index, and a SIMPER analysis (all species, including unknowns, were included).

As ANOSIM analysis does not allow for the inclusion of continuous variables (i.e. days since clearing), the data were grouped into five recovery periods (<6 months, 6–12 months, 1–2 years, 3–4 years, 4–5 years), allowing comparison between seismic and control plots for each category. Each recovery age category was represented by a different site, so individual comparison at each category reduces the confounding effect of site based differences, as comparisons were made within sites, not between them.

Differences in community composition (the presence or absence of each species) were presented using a non-metric multi-dimensional scaling (MDS), with Bray–Curtis similarity index.

The effect of clearing and recovery on individual vegetation characteristics were tested by fitting linear mixed-effects models, in the 'lme4' (ver. 1.1-13) package for R (Bates *et al.* 2014). In this analysis, time since clearing was expressed as the number of days since clearing (as opposed to the binned approach used in multivariate analysis). Vegetation characteristics were dealt with individually by including each as the response variable, with the treatment (seismic or control) and time since clearing included as fixed effects. Time since fire was included as a covariate, as it is likely to influence the vegetation parameters. All plots were sampled multiple times (Table 1), therefore 'plot ID' was included as a random factor to account for repeated sampling. Similarly, given the spatial separation between sites, and the fact that each site represented a different 'time since clearing', 'site ID' was included as a random factor to remove confounding effect of site based differences. To normalise the scale between variables, all continuous variables were scaled (subtract mean and divide by s.d.) before inclusion. Understorey cover and the understorey density at 30–100 cm were log-transformed to address heteroscedasticity, but all other variables were untransformed. Significance of first-order interaction between fixed variables and covariates was determined using an approximate F test, based on the Kenward-Rogers approximation in the package 'pbkrtest' (ver. 0.4-7) (Halekoh and Højsgaard 2014). Interaction terms that were not significant were excluded, to avoid potential inaccurate estimation of intercepts (Engqvist 2005). In order to test the significance of each predictor variable in the final model, an ANOVA with a Kenward-Rogers approximation was performed using the package 'lmerTest' (ver. 2.0-33) (Kuznetsova *et al.* 2015). For each model, the coefficient of determination (R^2) was calculated using the method outlined in Nakagawa and Schielzeth (2013), implemented using the R package 'MuMIn' (ver. 1.15.6) (Barton 2016), and the marginal R^2 (the variance explained by only the fixed effects) is presented.

Results

In total, 70 plant taxa were identified (48 to species and 22 to genus), with an additional 14 collections that could not be identified (Table 2). The summary data for all parameters measured on the survey plots, divided by time since clearing and treatment, are presented in Appendix 1, and examples of plots are shown in Fig. 2.

Vegetation structure

Differences in vegetation structure were visually apparent across the plots after <6 months (Fig. 2), but were less obvious thereafter. Significant differences between seismic and control plots were observed within six months of clearing (ANOSIM $r = 0.635$, $P < 0.001$). The percentage contribution of variables to the dissimilarity between seismic and control plots is shown in the SIMPER analysis, with observed differences due to the number of grasses (SIMPER, 25.4%), overstorey cover (19.9%), and understorey height (18.8%). In addition, the vegetation structure at the site was significantly different in 3–4 years (ANOSIM, $r = 0.12$, $P = 0.029$), due predominantly to greater overstorey cover (SIMPER 16.6%) and understorey height (12.4%) in control plots, and more shrubs (SIMPER 15.6%) on seismic plots. There was no difference in the vegetation structure between seismic and control plots after 6–12 months, 1–2 years, and 4–5 years.

Community composition

The most frequently occurring species were two trees, *Acacia tumida*, *A. eriopoda* and two grasses, *Sorghum plumosum* and *Aristida holathera*. Across all recovery periods, the community assemblage between seismic and control sites was significantly different (ANOSIM, $r = 0.04$, $P = 0.012$) due to *Sorghum plumosum* (SIMPER 6.3%) and *Acacia eriopoda* (5.8%) being present in more control plots than seismic. However, when each recovery period was analysed individually, the community assemblage was only different between seismic and control plots within six months since clearing (ANOSIM, $r = 0.702$, $P < 0.001$), predominantly due to *S. plumosum*, (SIMPER 21.3%), *A. eriopoda* (12.6%) and *Aristida* sp. (11.8%). There was no difference in the community assemblage between seismic lines cleared 6–12 months, 1–2 years, 3–4 years, and 4–5 years previously and their paired control plots (Fig. 3).

Individual vegetation characteristics

For understory cover, height and density (in all three height categories), and species richness, the interaction between treatment (seismic or control) and time since clearing was not significant, nor was time since clearing (Table 3). However, treatment had a significant effect with greater understory cover, height and density, and greater species richness in the control plots than in the seismic plots.

Table 2. Species identified and the number of plots (including resampled plots) in which each species was present. Botanical authorities are shown in brackets

Lifeform	Species	Control ($n = 50$)	Seismic ($n = 50$)
Grass	*Sorghum plumosum* (R.Br.) P.Beauv.	29	19
	Aristida holathera Domin	22	23
	Aristida sp.	17	12
	Chrysopogon pallidus (R.Br.) Steud.	13	10
	Eragrostis eriopoda Benth.	9	13
	Eriachne obtuse R.Br.	7	5
	Sorghum stipoideum (Ewart & Jean White) C.A.Gardner & C.E.Hubb.	6	6
	Eriachne sp.	3	3
	Chrysopogon fallax S.T.Blake	2	0
	Triodia sp.	1	1
	Aristida ingrata Domin	1	0
Herb/Shrub	*Trianthema pilosum* F.Muell.	10	12
	Spermacoce sp.	9	11
	Bonamia linearis (R.Br.) Hallier f.	9	10
	Polymeria sp.	11	8
	Waltheria indica L.	8	10
	Gyrostemon tepperi (H.Walter) A.S.George	11	5
	Senna notabilis (F.Muell.) Randell	7	7
	Corchorus sidoides F.Muell.	6	4
	Cullen sp.	6	4
	Bonamia sp.	4	5
	Ptilotus corymbosus R.Br.	4	3
	Ptilotus sp.	5	2
	Chamaecrista symonii Pedley	2	5
	Tephrosia sp.	2	4
	Zornia chaetophora F.Muell.	3	2
	Abutilon sp.	3	2
	Calandrinia sp.	2	3
	Hibiscus sp.	4	1
	Evolvulus alsinoides (L.) L.	1	3
	Mitrasacme sp.	3	1
	Indigofera linifolia (L.f.) Retz.	0	3
	Ptilotus polystachyus (Gaudich.) F.Muell.	2	1
	Scaevola parvifolia Benth.	0	3
	Tephrosia remotiflora Benth.	1	2
	Trichodesma zeylanicum (Burm.f.) R.Br.	3	0
	Solanum sp.	1	2
	Cleome tetrandra DC.	1	1
	Desmodium filiforme Zoll. & Moritzi	1	1
	Solanum lucani F.Muell.	1	1
	Dioscorea sp.	1	1
	Triumfetta sp.	1	1
	Crotalaria cunninghamii R.Br.	2	0
	Santalum lanceolatum R.Br.	1	1
	Senna costata (Bailey & C.T.White) Randell	1	1
	Phyllanthus sp.	2	0
	Cajanus marmoratus (Benth.) F.Muell.	0	1
	Calandrinia strophiolata (F.Muell.) Ewart, B.Rees & B.Wood	0	1
	Crotalaria medicaginea Lam.	0	1
	Goodenia sepalosa Benth.	0	1
	Heliotropium glabellum R.Br.	0	1
	Portulaca pilosa L.	0	1
	Tribulopis angustifolia R.Br.	1	0
	Corchorus sp.	1	0
	Euphorbia sp.	1	0
	Boerhavia sp.	1	0
	Clerodendrum floribundum R.Br.	1	0
	Polygala tepperi F.Muell.	0	1

(*Continued*)

Table 2. (Continued)

Lifeform	Species	Control ($n = 50$)	Seismic ($n = 50$)
	Sida cordifolia L.	0	1
	Sida rohlenae Domin	0	1
	12 Unknown spp.	18	21
Tree	*Acacia tumida* Benth.	30	29
	Acacia eriopoda Maiden & Blakely	26	11
	Dolichandrone occidentalis Jackes.	11	6
	Erythrophleum chlorostachys (F.Muell.) Baill.	4	2
	Atalaya hemiglauca (F.Muell.) Benth.	3	1
	Bauhinia cunninghamii (Benth.) Benth.	3	0
	Ehretia saligna R.Br.	1	1
	Melaleuca sp.	1	1
	Grevillea striata R.Br.	1	0
	Atalaya sp.	1	0
	Two unknown spp.	5	5
	Total count of species	61	59

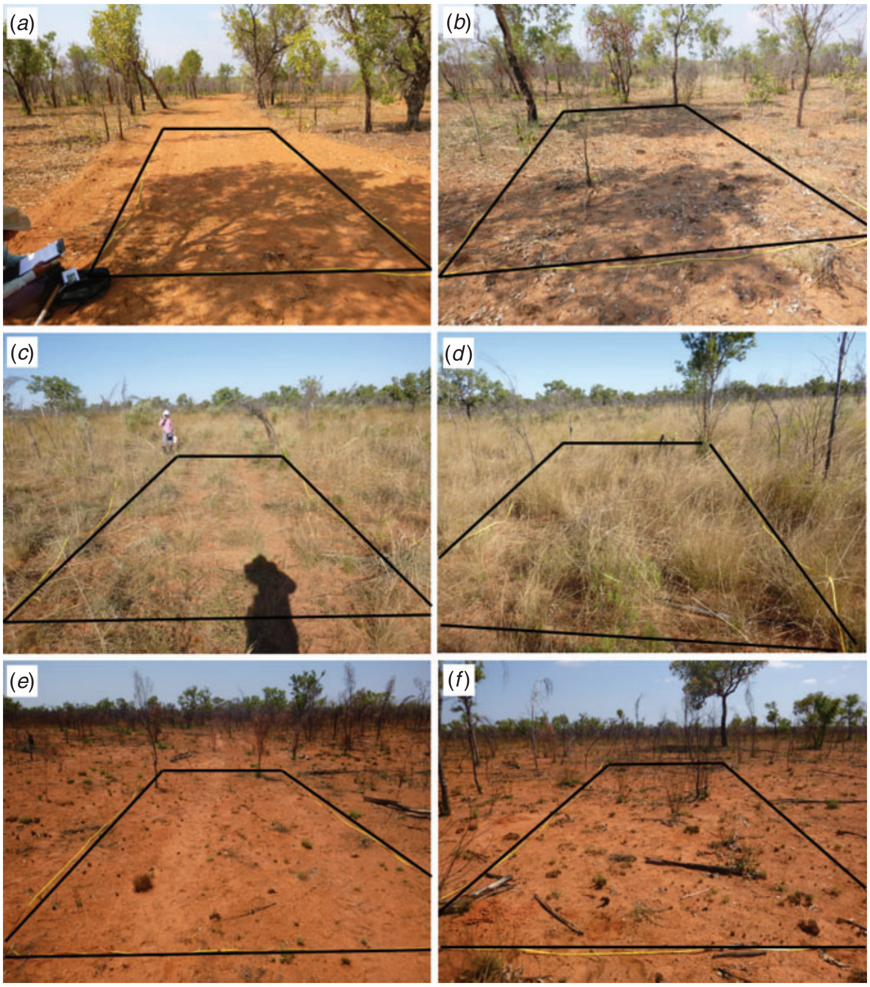

Fig. 2. Examples of 4 × 10 m vegetation recovery plots, with seismic plots on the left and control plots on the right; (*a*, *b*) Yakka Munga, 50 days after clearing; (*c*, *d*) Yulleroo West, 4–5 years after clearing (*e*, *f*) the same plots as (*c*, *d*) after a fire burnt the site.

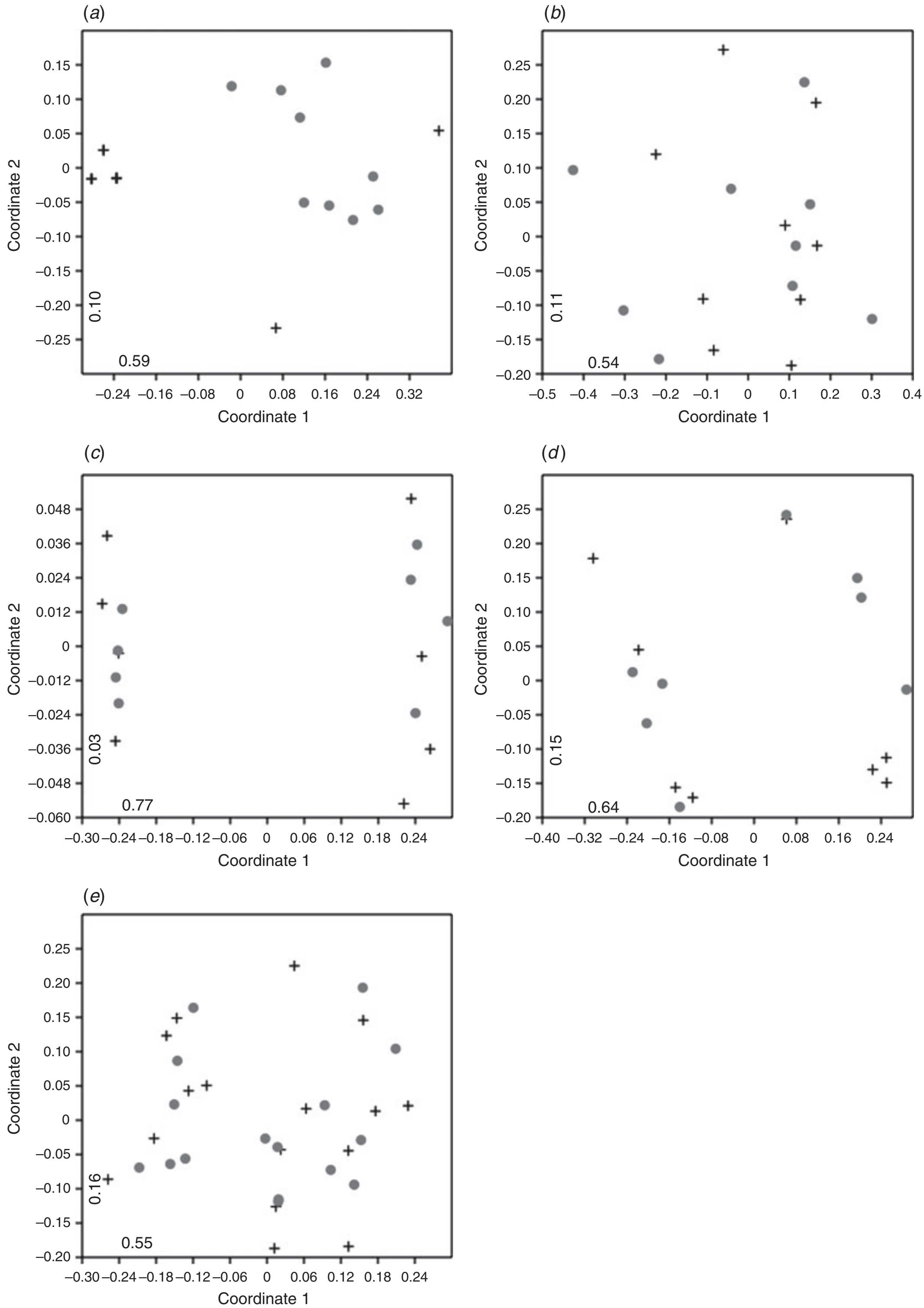

Fig. 3. Multidimensional scaling (MDS) plots showing the difference in community composition between seismic (grey dots) and control (black crosses) plots, across each time since clearing; (*a*) <6 months. (months), (*b*) 6–12 months, (*c*) 1–2 years, (*d*) 3–4 years, (*e*) and 4–5 years. The pronounced difference (gap) in (*c*), and to a lesser extent in (*d*), is due to different times since fire; six months vs 12 months since burn and 9–18 months vs 42–50 months. since burn respectively. Stress values for each coordinate are shown in bottom left of each plot.

Table 3. Results of linear mixed effect modelling of the effect of clearing, time since clearing and time since fire on individual vegetation characteristics

Covariates, and covariate interactions are included to account for variation according to fire history; however, they are not directly tested in this analysis. R^2 is shown indicating the goodness of fit of the model

Response variable	Treatment	Time since clearing	Treatment*Time since clearing	Time since fire	Time since clearing*Time since fire	R^2
		Fixed factors			Covariates	
Understorey cover	($F_{1,74} = 9.074$, $P = 0.004$)	($F_{1,23} = 0.949$, $P = 0.340$)	($F_{1,74} = 0.052$, $P = 0.820$)	($F_{1,29} = 4.746$, $P = 0.038$)	($F_{1,33} = 6.403$, $P = 0.016$)	0.155
Understorey height	($F_{1,75} = 11.581$, $P < 0.01$)	($F_{1,2=18} = 3.548$, $P = 0.076$)	($F_{1,275} = 0.039$, $P = 0.845$)	($F_{1,27.} = 0.014$, $P = 0.908$)	–	0.156
Overstorey cover	($F_{1,75} = 2.383$, $P = 0.127$)	($F_{1,26} = 0.082$, $P = 0.777$)	($F_{1,75} = 1.959$, $P = 0.166$)	($F_{1,24} = 10.264$, $P = 0.004$)	–	0.086
Understorey density 0–10 cm	($F_{1,75} = 5.479$, $P = 0.022$)	($F_{1,26} = 1.615$, $P = 0.215$)	($F_{1,75} = 0.355$, $P = 0.553$)	($F_{1,25} = 5.628$, $P = 0.025$)	–	0.104
10–30 cm	($F_{1,75} = 4.728$, $P = 0.033$)	($F_{1,25} = 1.879$, $P = 0.183$)	($F_{1,75} = 0.916$, $P = 0.341$)	($F_{1,26} = 4.645$, $P = 0.041$)		0.106
30–100 cm	($F_{1,75} = 16.355$, $P < 0.001$)	($F_{1,23} = 3.860$, $P = 0.062$)	($F_{1,75} = 2.613$, $P = 0.110$)	($F_{1,29} = 2.403$, $P = 0.132$)	($F_{1,32} = 5.619$, $P = 0.024$)	0.214
Count of ind. plants Grasses	($F_{1,75} = 2.313$, $P = 0.133$)	($F_{1,267} = 0.007$, $P = 0.934$)	($F_{1,75} = 5.124$, $P = 0.026$)	($F_{1,24} = 4.934$, $P = 0.036$)	–	0.082
Shrubs	($F_{1,75} = 0.327$, $P = 0.569$)	($F_{1,7} = 3.624$, $P = 0.096$)	($F_{1,75} = 0.031$, $P = 0.862$)	($F_{1,22} = 0.132$, $P = 0.720$)	–	0.106
Trees <3 m	($F_{1,75} = 0.451$, $P = 0.504$)	($F_{1,25} = 0.337$, $P = 0.566$)	($F_{1,75} = 0.741$, $P = 0.392$)	($F_{1,28} = 0.047$, $P = 0.830$)	–	0.019
Tree >3 m	($F_{1,75} = 0.008$, $P = 0.930$)	($F_{1,24} = 0.467$, $P = 0.500$)	($F_{1,75} = 13.866$, $P < 0.001$)	($F_{1,23} = 0.398$, $P = 0.534$)	–	0.032
Species richness	($F_{1,75} = 4.358$, $P = 0.040$)	($F_{1,25} = 3.536$, $P = 0.072$)	($F_{1,75} = 0.138$, $P = 0.710$)	($F_{1,26} = 1.963$, $P = 0.173$)	–	0.105

The interaction between treatment and time since clearing was significant for the number of grasses and the number of trees >3 m, indicating that the difference between treatments changed over time since clearing. The number of grasses was initially lower for seismic plots after <6 months (the seismic plots were bare ground), but by 6–12 months, and thereafter was similar to the control plots. Although there is a lack of replication of recovery periods among sites, the average number of grasses within the same seismic plots within the Yakka Munga site was 0 after clearing, and 58 after 6–12 months, and on control plots the number of grasses was 58 within six months of clearing, and 58 after 6–12 months. After 4–5 years since clearing, there were more trees >3 m on recovering seismic lines. Time since fire (covariate) had a significant effect on understorey cover and density (0–10 cm and 10–30 cm), overstorey cover, and the number of grasses; however, all other effects were non-significant. The interaction between time since clearing and time since fire was removed as a non-significant interaction during modelling of most variables, but there was a significant effect of the interaction on understory cover and understorey density at 30–100 cm. Both of these understorey variables are high when there has been a long time since clearing and since fire.

Discussion

The structure and community composition of the vegetation on seismic lines usually recovered after 6–12 months such that there were no detectable differences from adjacent undisturbed plots. Although there was complete separation between recovery periods (each period was represented by a different site), comparisons were only made between control and seismic plots within the same site.

There was a significant difference in vegetation structure between seismic and control plots after 3–4 years at the one site assessed at that time: Yakka-Munga 2D. There, the overstorey cover and understorey height were greater in control plots than in seismic plots. The lagged recovery response of these characteristics, compared with other sites, may be due to greater vehicle traffic immediately following clearing. Generally, 2D seismic surveys are made up of single, long seismic lines, that only intersect with other seismic lines at one or two points (often kilometres apart). In contrast, 3D lines intersect other seismic lines every 200 m. As a result, 2D lines are likely to receive a greater percentage of vehicle traffic associated with the survey, given the reduced availability of access. Greater vehicle use may compact soil and slow the recovery of tracks (Webb *et al.* 1986). However, site-based habitat differences may also contribute to this result. As such, it is important to compare recovery within sites rather than between in this discussion.

The vegetation structure and community composition were generally similar between seismic and control plots from 6–12 months to 4–5 years since clearing, although the response of individual vegetation characteristics was variable. Understorey cover, height, and density (three height categories), and species richness showed significant differences between seismic and control plots across all times since clearing. However, the number of grasses recovered well within 6–12 months, being different at <6 months but similar thereafter. This suggests that the number of germinating grasses are similar in seismic and control plots; however, their growth is slower on seismic plots than control plots.

We did not directly test for the presence of a ‘border effect’, where vegetation recolonisation occurs faster close to adjacent uncleared vegetation. In fact, the origin of recolonising vegetation was not of interest during this study – we were primarily interested in how fast or successfully vegetation on seismic lines recovered. However, during field surveys we did not record greater recolonisation at the border of plots than in the centre. This may be interpreted in two ways, either there was little observable border effect in the current study, or the plots were so small (~4 m wide) that the entire plot is considered within the ‘border’, and therefore recolonisation occurs uniformly.

We suggest that the rates of recovery of understorey on seismic lines may be slowed by cattle, which preferentially use seismic lines (Dawson *et al.* 2018). Use by both people (Fiori and Zalba 2003) and livestock (Klepacki *et al.* 1985) have previously been shown to inhibit recovery of seismic lines. As cattle were present throughout all sites in the current study, no comparison between areas with and without cattle can be made. Future studies should investigate the effect of excluding cattle from recovering seismic lines.

The number of trees was slow to recover, but tree number was actually greater than control plots after 4–5 years. Often, *Acacia* spp. were present in dense stands on recovering seismic lines, indicating that in some instances the growth of this species may have been promoted by clearing, or by disturbance to topsoil. Similarly, windrows of pushed vegetation on tracks in Pindan vegetation are colonised by thick stands of *Acacia* spp. and *Senna* spp. It is important to note that the 4–5 year recovery age is represented by Yulleroo sites only, and may represent site-based differences; however, we consider this unlikely given the similarities in vegetation types between sites.

The recovery of vegetation after clearing of seismic lines has been predominantly studied in North America and is typically quite slow (Fiori and Zalba 2003; van Rensen *et al.* 2015), sometimes in excess of 35 years (Lee and Boutin 2006). In comparison, the vegetation recovery was faster in the current study; however, the difference between tropical savannah of north-west Australia and boreal plains of North America make such differences unsurprising, and render comparisons largely arbitrary.

Fire history had a significant effect on many of the understorey characteristics as well as overstorey cover and confounded the effects of clearing. Community composition analysis at 1–2 years and 3–4 years (Fig. 3*c*, *d*), show two clear groups of plots; however, these differences were not accounted for by treatment (see Fig. 3*a* for comparison). This grouping was attributable to different fire ages present within the same time since clearing. It was not possible to control the incidence of fire in the current study, as we were working on a commercial property that uses fire to manage grass growth for cattle forage. Future studies of vegetation recovery in Pindan should consider fire history as a significant variable.

The present study was limited by the availability of sites that were subject to a seismic survey over a range of different times. We used sites which represented different times since clearing, potentially introducing confounding effects of site. Accordingly, comparisons in vegetation structure and assemblage were made at each site at specific times since clearing. Similarly, by including site as a random factor in linear mixed-effects modelling, the confounding effects of site were removed. A longitudinal study, sampling seismic lines from soon after clearing to full recovery, would be optimal for further testing recovery rates of seismic lines.

It is very likely that variations in annual rainfall will strongly influence the rate of recovery of seismic lines. Generally, rainfall over the time included in this study was within 10% of the average rainfall (Table 1), so the slow recovery observed at some sites is unlikely to be explained entirely by poor rainfall. However, it is important to note that many weather stations in the area were missing rainfall data during the period from 2011 to 2016. Consequently, data from the Broome Airport Weather Station, 65 km from the nearest study site, were used. These may not accurately represent the total, or patchiness of the rainfall at each site.

Highly seasonal and relatively predictable rainfall (compared with more arid areas), combined with a long history of regular fire, may influence the recovery patterns observed in the current study. Pindan vegetation follows a 3–5 years post-fire succession cycle. The dominant species (e.g. *Eucalyptus* spp., *E. chlorostachys*) re-establishes canopies within one year; annual Sorghum grasses increases 1–2 years post fire, before the re-establishment of perennial tussock and hummock grasses; and the *Acacia* spp. dominated canopy recovers after 3–5 years (Radford and Fairman 2015). The frequent fires that occur in Pindan vegetation, coupled with the fast recovery rate from fire, suggest that this vegetation type is well equipped to recover quickly from perturbations.

In the present study, there was no difference in vegetation structure and species assemblage after ~1 year since clearing; however, individual understorey density and cover parameters differed in their response, with the understorey recovering slowly. Time since fire had the most profound impact on all individual vegetation characteristics. We suggest that because Pindan vegetation has evolved with frequent burning and predictable annual rainfall in the West Kimberley, it recovers quickly from disturbances such as raised-blade clearing and fire.

Conflicts of interest

This study was funded by Buru Energy, the company that commissioned the seismic survey. KW is employed by Buru Energy, and SD has previously consulted for Buru Energy.

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References

Barton, K. (2016). MuMIn: multi-model inference. R package ver. 1.15. 6. Available at: https://cran.r-project.org/web/packages/MuMIn/MuMIn.pdf (accessed 6 December 2019).

Bastin, G., and the ACRIS Management Committee (2008). Rangelands 2008 – Taking the Pulse. Published on behalf of the ACRIS Management Committee by the National Land and Water Resources Audit, Canberra.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Grothendieck, G., Green, P., and Bolker, M. B. (2014). Package 'lme4.' (R Foundation for Statistical Computing: Vienna, Austria.)

Bureau of Meteorology (2019). Climate Data Online, Australian Bureau of Meteorology. Available at: http://www.bom.gov.au/climate/data/ (accessed 10 October 2019).

Dawson, S. J., Adams, P. J., Moseby, K. E., Waddington, K. I., Kobryn, H. T., Bateman, P. W., and Fleming, P. A. (2018). Peak hour in the bush: linear anthropogenic clearings funnel predator and prey species. *Austral Ecology* **43**, 159–171. doi:10.1111/aec.12553

Engqvist, L. (2005). The mistreatment of covariate interaction terms in linear model analyses of behavioural and evolutionary ecology studies. *Animal Behaviour* **70**, 967–971. doi:10.1016/j.anbehav.2005.01.016

Fiori, S. M., and Zalba, S. M. (2003). Potential impacts of petroleum exploration and exploitation on biodiversity in a Patagonian Nature Reserve, Argentina. *Biodiversity and Conservation* **12**, 1261–1270. doi:10.1023/A:1023091922825

Goosem, M. (2007). Fragmentation impacts caused by roads through rainforests. *Current Science* **92**, 1587–1595.

Halekoh, U., and Højsgaard, S. (2014). A Kenward-Roger approximation and parametric bootstrap methods for tests in linear mixed models – the R package pbkrtest. *Journal of Statistical Software* **59**, 1–32. doi:10.18637/jss.v059.i09

Hammer, Ø., Harper, D. A. T., and Ryan, P. D. (2001). PAST: Paleotological Statistics software package for education and data analysis. *Palaeontologia Electronica*. Available at: https://folk.uio.no/ohammer/past/ (accessed 15 June 2017).

Kenneally, K. F., Edinger, D. C., and Willing, T. (1996). 'Broome and Beyond: Plants and People of the Dampier Peninsula, Kimberley, Western Australia.' (Western Australia: Department of Conservation and Land Management: Como, WA.)

Klepacki, N., Black, S., and Marchant, M. (1985). 'Impact of Petroleum Exploration Activity on Range Resources and Pastoral Pursuits in the West Kimberley.' (WA Department of Agriculture, Division of Resources Management: Perth, WA.)

Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2015). Package 'lmerTest'. R package ver. 2. Available at: https://cran.r-project.org/web/packages/lmerTest/lmerTest.pdf (accessed 6 December 2019).

Lee, P., and Boutin, S. (2006). Persistence and developmental transition of wide seismic lines in the western Boreal Plains of Canada. *Journal of Environmental Management* **78**, 240–250. doi:10.1016/j.jenvman.2005.03.016

McGregor, H. W., Legge, S., Jones, M. E., and Johnson, C. N. (2014). Landscape management of fire and grazing regimes alters the fine-scale habitat utilisation by feral cats. *PLoS One* **9**, e109097. doi:10.1371/journal.pone.0109097

Nakagawa, S., and Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution* **4**, 133–142. doi:10.1111/j.2041-210x.2012.00261.x

O'Loughlin, T. (1989). The environment – not just a greenie issue. *Australian Gas Journal* **53**, 11–15.

R Core Team (2018). 'R: A language and environment for statistical computing.' (R Foundation for Statistical Computing: Vienna, Austria.) Available at: http://www.R-project.org/ (accessed 6 December 2019).

Radford, I. J., and Fairman, R. (2015). Fauna and vegetation responses to fire and invasion by toxic cane toads (*Rhinella marina*) in an obligate seeder-dominated tropical savanna in the Kimberley, northern Australia. *Wildlife Research* **42**, 302–314. doi:10.1071/WR14259

Reed, R. A., Johnson-Barnard, J., and Baker, W. L. (1996). Contribution of roads to forest fragmentation in the Rocky Mountains. *Conservation Biology* **10**, 1098–1106. doi:10.1046/j.1523-1739.1996.10041098.x

Russell-Smith, J., Yates, C., Edwards, A., Allan, G. E., Cook, G. D., Cooke, P., Craig, R., Heath, B., and Smith, R. (2003). Contemporary fire regimes of northern Australia, 1997–2001: change since Aboriginal occupancy, challenges for sustainable management. *International Journal of Wildland Fire* **12**, 283–297. doi:10.1071/WF03015

Taylor, D. (1992). Blina Oilfield, Canning Basin, case history. *Exploration Geophysics* **23**, 467–480. doi:10.1071/EG992467

Thackway, R., and Cresswell, I. (1995). 'An Interim Biogeographic Regionalisation for Australia: A Framework for Establishing the National System of Reserves. Ver. 4.0.' (Australian Nature Conservation Agency: Canberra.)

van Rensen, C. K., Nielsen, S. E., White, B., Vinge, T., and Lieffers, V. J. (2015). Natural regeneration of forest vegetation on legacy seismic lines in boreal habitats in Alberta's oil sands region. *Biological Conservation* **184**, 127–135. doi:10.1016/j.biocon.2015.01.020

Webb, R. H., Steiger, J. W., and Wilshire, H. G. (1986). Recovery of compacted soils in Mojave Desert ghost towns. *Soil Science Society of America Journal* **50**, 1341–1344. doi:10.2136/sssaj1986.03615995005000050051x

Appendix 1. Mean and s.d. of all parameters measured, displayed by time since clearing and treatment

					Touch pole				Number of plants in each strata				
Treatment	Time since fire (months)	Understorey cover (%)	Understorey height (cm)	Overstorey cover (%)	0–10 cm	10–30 cm	30–100 cm	Grasses	Shrubs	Trees <3	Trees >3	Species richness	
<6 month	Control	19.5 ± 16.8	3 ± 3.9	40 ± 0	1.4 ± 1.5	3.5 ± 2.9	4.7 ± 2.9	2.4 ± 1.5	58.4 ± 36.6	3.4 ± 3.9	7.6 ± 8.6	2.7 ± 2.8	4.3 ± 1.3
	Seismic	19.5 ± 16.8	0.1 ± 0.3	13.3 ± 20	0.7 ± 1.6	0 ± 0	0.1 ± 0.3	0.1 ± 0.3	0 ± 0	0 ± 0	1.4 ± 4.3	0 ± 0	0.2 ± 0.4
6–12 month	Control	26.1 ± 17.1	2.2 ± 1.6	40 ± 0	2 ± 1.3	6.8 ± 7.4	8.2 ± 6.4	4.7 ± 3.9	58 ± 31	37.6 ± 31.1	11.2 ± 14.1	4.2 ± 6.7	6.3 ± 2
	Seismic	26.1 ± 17.1	1.5 ± 1.3	40 ± 0	1.3 ± 0.7	3.6 ± 2.9	3.8 ± 2	0.8 ± 1.2	58.6 ± 37.1	28.3 ± 29.1	13.8 ± 18.8	0 ± 0	7.4 ± 2.3
1–2 years	Control	9.6 ± 3.8	34.6 ± 26.8	61.8 ± 18.1	1.1 ± 0.6	15.1 ± 9.2	14.3 ± 6.5	15.2 ± 8.3	98.7 ± 3.5	11.3 ± 10	20.1 ± 13	1.6 ± 4.2	6.3 ± 2.3
	Seismic	9.6 ± 3.8	14 ± 13.5	48.7 ± 16.2	1.2 ± 1.6	9.3 ± 5.9	9.2 ± 5.5	7.1 ± 5.8	90 ± 18.5	16.3 ± 11	22.5 ± 20	0 ± 0	6.5 ± 2.6
3–4 years	Control	28.9 ± 18	8.3 ± 16.9	58.1 ± 39	2.3 ± 1.6	4.3 ± 2.6	4 ± 3.3	7 ± 9.5	28.5 ± 36	19.6 ± 33.4	6.6 ± 3.8	1 ± 1.4	5.7 ± 1.2
	Seismic	28.9 ± 18	7.1 ± 9.6	40 ± 0	0.6 ± 0.5	7.5 ± 5.3	9.2 ± 7.1	5.3 ± 5.1	53.6 ± 32.7	20.7 ± 24.4	15.5 ± 14.5	0.3 ± 0.5	4 ± 1
4–5 years	Control	7.5 ± 4.1	25.5 ± 25.8	60.3 ± 37.6	0.5 ± 1.3	11.8 ± 7.9	12.8 ± 10.4	12.1 ± 9.6	82.3 ± 33.5	34.5 ± 18.5	3.5 ± 3.5	0.2 ± 0.7	8.3 ± 2.8
	Seismic	7.5 ± 4.1	9.4 ± 11.5	44.3 ± 11.9	1 ± 1.7	8.2 ± 6.9	9 ± 7.4	5.8 ± 4.8	77 ± 29.4	30.9 ± 22.7	4.1 ± 4.2	5 ± 13.8	7.5 ± 2.7