SHORT TERM SOIL AND VEGETATION RECOVERY AFTER *ACACIA MEARNSII* REMOVAL IN VHEMBE BIOSPHERE RESERVE, SOUTH AFRICA

RUWANZA, S.[1*] – TSHILILO, K.[2]

[1]*Department of Environmental Science and Centre for Invasion Biology, Rhodes University P. O. Box 94, Grahamstown 6140, South Africa*

[2]*Department of Ecology and Resource Management, University of Venda Private Bag X5050, Thohoyandou 0950, South Africa*

**Corresponding author*
e-mail: ruwanza@yahoo.com; phone: +27 46 603 7009; fax: +27 46 603 7574

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Abstract. Short term monitoring of soil and vegetation recovery following alien plant removal is required to reveal how ecological restoration is progressing. This study examined the recovery of soil physical properties and vegetation following *Acacia mearnsii* removal at Zvakanaka farm in Limpopo Province, South Africa. Soil and vegetation measurements were conducted in paired cleared, invaded and natural sites on 10 x 10 m plots. Results of the study show significantly ($P < 0.001$) higher soil moisture content in invaded and natural compared to cleared sites. Soil penetration was significantly ($P < 0.001$) higher in cleared than invaded and natural sites. Both infiltration rate and hydraulic conductivity showed no significant ($P > 0.05$) difference between the three sites. Strongly repellent soils were recorded in cleared sites only. Results showed a significant ($P < 0.05$) increase in measured diversity indices (species richness, Shannon-Wiener, Simpson's and evenness index) in cleared and natural than in invaded sites. However, most secondary woody invasive alien plants were recorded in cleared sites. The study concludes that *A. mearnsii* clearing triggers varying changes in soil physical properties. Although native plants are present in cleared sites, recovery may be hampered by the growth of secondary woody invasive alien plants.
Keywords: *post-clearing monitoring, invasive plants, ecosystem repair, revegetation, secondary invaders*

Introduction

Invasion by Australian *Acacia* species in South Africa has resulted in biodiversity loss (Werner et al., 2010; Gaertner et al., 2011), altered ecosystem functioning and service provisioning (Kull et al., 2008; Le Maitre et al., 2011). *Acacias* are known to stimulate changes in soil communities (Yelenik et al., 2004; Gaertner et al., 2011) which enables them to dominate native species, resulting in native species displacement (Le Maitre et al., 2011). Negative impacts of *Acacia* invasion on biodiversity and ecosystems ultimately affect human well-being (Le Maitre et al., 2011). For example, stands of *A. mearnsii* invasion in South Africa have been shown to utilize more water compared to fynbos biome native vegetation (Dye et al., 2001; Dye and Jarmain, 2004), this resulting in water reduction for agriculture, industry, recreation, conservation and domestic use (Görgens and van Wilgen, 2004). Also, the high biomass of *Acacia* species has been known to increase fire severity (van Wilgen and Richardson, 1985), thus not only affecting re-sprouting native plants but also housing properties.

Management interventions to address the impacts of *Acacia* invasions, and may other invasive plants, are underway in South Africa (Le Maitre et al., 2011). The Working for

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Water (WfW) programme, a government initiative to manage and control invasives, has adopted a passive restoration approach which aims to remove the invader as well as limit and prevent their regeneration (Le Maitre et al., 2002; Esler et al., 2008; van Wilgen et al., 2012). However, the passive restoration approach by WfW has yielded mixed results when it comes to soil and vegetation recovery (Galatowitsch and Richardson, 2005; Blanchard and Holmes, 2008; Pretorius et al., 2008; Ruwanza et al., 2013a; Nsikani et al., 2017; Fill et al., 2018). As a result, there is a need to improve understanding of factors that hinder or facilitate soil and vegetation recovery after alien plant clearing.

For ecological restoration to be successful, periodic monitoring of cleared areas is required to reveal how restoration is progressing and were management interventions are required (Ruiz-Jaen and Aide, 2005; Fill et al., 2018). However, a complicating factor in monitoring ecological restoration projects is the defining of appropriate variables to be measured (Ruiz-Jaen and Aide, 2005). In cases were the restoration goal is to return natural vegetation structure, function and processes to reference condition, monitoring native vegetation diversity and soil processes e.g. physical (soil structure), chemical (soil nutrients) and biological (soil bacteria) becomes important (Ruiz-Jaen and Aide, 2005; Wortley et al., 2013). Unfortunately, both short and long-term monitoring in most WfW alien clearing projects is rarely done (Fill et al., 2018).

Methodological constraints associated with monitoring biological invasions have been reported in the past (Stricker et al., 2015). Although most observational studies compare differences between invaded, uninvaded and cleared areas (Fill et al., 2018), a more appropriate method is to observe changes before and after invasion (Stricker et al., 2015). The challenges associated with before and after observational experiments is time, given that invasion could have occurred several years ago, and observations prior-invasion might not have been done. Observing changes between invaded, uninvaded and cleared areas does not allow deduction on causation to be made, because observed differences may be driven by other ecosystem processes and not necessarily by invasive plants (MacDougall and Turkington, 2005; Guido and Pillar, 2015; Guido and Pillar, 2017). Despite these methodological limitations, observing invaded, natural and cleared areas can assist in generalizing recovery patterns that can be used to inform recovery trajectories. This study present findings on soil and vegetation recovery post *A. mearnsii* removal. The goal is to assess changes in both soil physical properties and native vegetation diversity after *A. mearnsii* clearing, to provide a picture of ecological recovery. Results will guide future ecological restoration initiatives following *A. mearnsii* removal.

Materials and methods

Study area and site identification

The study area was Zvakanaka farm (22°97'72.23"S and 29°95'30.90"E; *Fig. 1*), some 10 km outside Louis Trichardt in Limpopo Province, South Africa. The farm is used for tourism purposes, with a few guest houses and camp sites. Vegetation in the farm is classified as both Soutpansberg Summit Sourveld and Soutpansberg Mountain Bushveld by Mucina and Rutherford (2006). Soils in the study area are derived from shale and siltstones of the Soutpansberg group (Mucina and Rutherford, 2006). They are generally shallow and drain quickly leading to leached and acidic soils. Average annual rainfall is between 450 and 900 mm, with most rain falling in summer between October

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and March. Temperature ranges from approximately 5°C in winter to 35°C in summer (Mucina and Rutherford, 2006).

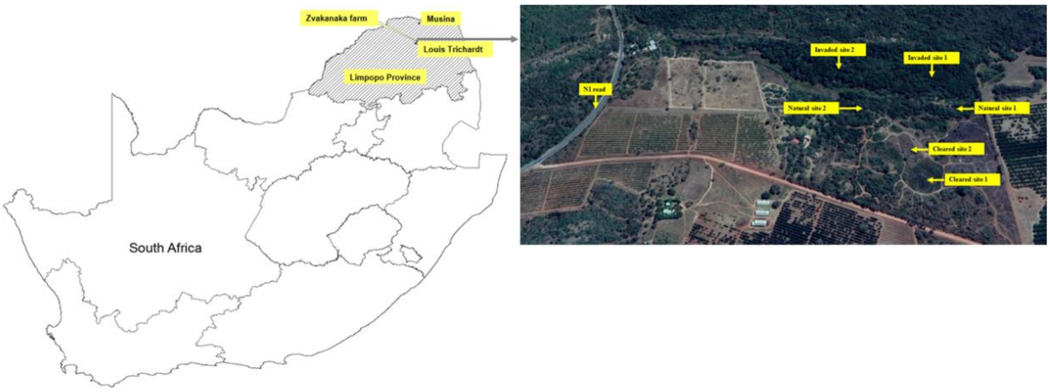

Figure 1. *The location of the study area in Zvakanaka farm located outside Louis Trichardt in the Limpopo province of South Africa*

Within Zvakanaka farm three invasion conditions (approximately 2 km apart), namely cleared, natural and invaded were identified (*Table 1*). Two sites were setup at each of the above-mentioned invasion condition (paired sites were approximately 50 m apart). Due to the small size of the cleared area, only two sites were possible in the cleared area, therefore the experimental design was limited to site pairing per each of the above-mentioned invasion condition.

Table 1. *Characteristics of the study area showing the three invasion conditions namely cleared, invaded, and natural sites. Each site's Universal Transverse Mercator coordinate location is shown*

Invasion condition	Site name	Coordinates	Site characteristics
Cleared site	CS 1	22°58'47.02"S, 29°57'25.77"E	- Cleared of *A. mearnsii* and other woody invasive in early 2016 - Follow-up clearing treatment in progress
	CS 2	22°58'46.86"S, 29°57'21.37"E	
Natural site	NS 1	22°58'38.59"S, 29°57'21.70"E	- Dominated by stands of native species - Canopy cover > 60%
	NS 2	22°58'38.32"S, 29°57'17.36"E	
Invaded site	IS 1	22°58'32.64"S, 29°57'26.08"E	- Invaded by huge stands of *A. mearnsii* with little underground vegetation - Canopy cover > 60%
	IS 2	22°58'32.43"S, 29°57'20.54"E	

Cleared sites had *A. mearnsii* (and any other existing woody invasives) removed by WfW in early 2016 (Maytham, 2017, personal communication). Clearing by WfW involved the felling of alien trees and herbicide application on cut stumps to prevent re-growth. Cleared plant material were stack burnt on site. The cleared area had received only one follow-up treatment (meant to remove all alien plant saplings) since the initial clearing was conducted. No soil or vegetation surveys were conducted before WfW clearing, therefore, the condition of the cleared areas prior both invasion and clearing is

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unknown. Close to the cleared site is a mature stand of *A. mearnsii* that is yet to be cleared. The stand which is dominated by *A. mearnsii* represented the invaded site. In-between the cleared and invaded sites, dense stands of native species exist, and these acted as the natural reference sites. Therefore, the three invasion conditions comprised two cleared sites where *A. mearnsii* was removed in 2016, two invaded sites where *A. mearnsii* dominate (canopy cover above 60%), and two natural sites where stands of native species dominate (canopy cover above 60%).

Survey design and field sampling

In winter 2017, five randomly distributed replicated plots, each measures 10 m x 10 m, were set-up on each of the above-mentioned site. A total of 30 plots were setup (5 plots x 2 sites x 3 invasion conditions). Within each plot soil and vegetation surveys were conducted. Soil cores (30 in total) measuring 10 cm in diameter and 10 cm depth were collected from the center of each plot for gravimetric soil moisture and soil water repellency measurements which were conducted under laboratory conditions at the University of Venda. Before the above-mentioned laboratory measurements were conducted, soils were first sieved using a 2-mm sieve to remove debris. Gravimetric soil moisture (expressed as a percentage) was assessed by weighing wet soils, dry them in an oven at 105°C for 72 hours, then re-weighing them to obtain the water content (Black, 1965). The Water Droplet Penetration Time (WDPT) method was used to measure soil water repellency (Doerr and Thomas, 2000). Sieved soils were air dried for seven days under laboratory conditions (temperature 18±2°C which is the average Thohoyandou winter temperatures) before being set into petri dishes and levelled. The WDPT test was conducted by placing five water droplets on the soil surface and record the time taken for the water droplet to penetrate the soil (Doerr and Thomas, 2000). The penetration time was averaged to represent the WDPT for each soil sample. Soils were classified based on repellecy classes suggested by Bisdom et al. (1993) (see *Table 2*).

Table 2. *Classification of soil water repellency based on the The Water Droplet Penetration Time (WDPT) method*

Classification	The Water Droplet Penetration Time (in seconds)
Non-repellent	< 5
Slightly water repellent	6 - 60
Strongly water repellent	61 - 600
Severely water repellent	601 - 3600
Extremely water repellent	> 3 601

Soil penetration resistance levels and infiltration rates were measured under field conditions 30 cm away from soil collection points at the center of each plot. Soil penetration resistance levels were measured using a pocket penetrometer (SOILTEST, Inc., Evanston, Illinois, USA). To take measurements, the penetrometer is pushed into the soil and a metal ring is pushed up to mark the resistance value in kg cm^{-2} (Leung and Meyer, 2003). Infiltration rate and hydraulic conductivity in the soil were measured with a mini disk infiltrometer (Decagon Devices, Pullman, WA, USA). The infiltrometer is an acrylic tube with a semipermeable plastic disk, a suction tube inside, and a rubber stopper (Latorre et al., 2013). Suction rate was set at 2.0 cm in this study. Both the upper and lower chambers were filled with water before taking measurements

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on flat soil surfaces following the hand removal of litter. The water infiltration rate was measured from the drop of water level in the lower chamber in mL after every 30-s interval for 5 minutes. The cumulative infiltration rate over time was determined using the method suggested by Zhang (1997). Similarly, hydraulic conductivity was calculated from the infiltration data using the van Genuchten-Zhang method (Zhang, 1997, 1998). For more information see the mini disk infiltrometer manual which can be found at Decagon Devices (2014).

A detailed vegetation survey was conducted in all plots. Richness of trees and shrubs was determined from counts of the total individual plant species in the plot. Richness of herbs and graminoids was determined from counts of all the individuals in a 1 m^2 quadrat placed at the center of the plot. All recognized plant species in the plot were collected for identification at University of Venda herbarium in the Department of Botany. Plant species were assigned to four broad growth form classes based on morphology and height. The four-growth form used in this study are trees, shrubs, forbs and grasses, as described by Goldblatt and Manning (2000).

Data analysis

To avoid pseudo-replication, soil and vegetation results from the ten plots per invasion condition (two sites x five plot replicates) were averaged. Gravimetric soil moisture, soil penetration resistance levels, infiltration rates**,** and hydraulic conductivity for the different sites, were analysed using one-way ANOVA in Statistica version 13.1 (Statsoft Inc, 2016). For each site, species richness, Shannon-Wiener diversity index (H'), Simpson's index of diversity and Evenness index (J) using Pielou's 'J' (Zar, 1996) were calculated per plot and used to examine the effects of alien plant clearing on species diversity. The effects of the above-mentioned diversity indices on invesion conditions were compared using one-way ANOVA in Statistica. Proof of normality and homogeneity of varience were tested using Kolmogorov-Smirnov tests and Levene test respectively. Data was normally distributed and where ANOVAs were significant, Tukey's HSD unequal n test was used to determine differences between sites. Soil water repellency classes were analyzed using the Chi-squared test. Plant species occupancy frequencies, which is the number of species occupying different plots per site independent of their abundance, were calculated as a percentage for all the identified species at each site (presented as *Appendix*).

Results

Comparisons between the three sites showed significant ($P < 0.001$) differences in gravimetric soil moisture levels (*Fig. 2A*). Soil moisture levels were higher in invaded and natural sites than in cleared sites. Contrary, soil penetration resistance levels were significantly ($P < 0.001$) higher in cleared sites than in the invaded and natural sites (*Fig. 2B*). The average infiltration rate in the cleared and natural sites was 3.2 ± 0.58 cm and 3.2 ± 1.11 cm respectively after 5 minutes, compared to 2.0 ± 1.26 cm in the invaded sites. However, the above-mentioned results on infiltration rates showed no significant ($P > 0.05$) differences between the three sites (*Fig. 2C*). Similarly, soil hydraulic conductivity showed no significant differences between the three sites (*Fig. 2D*).

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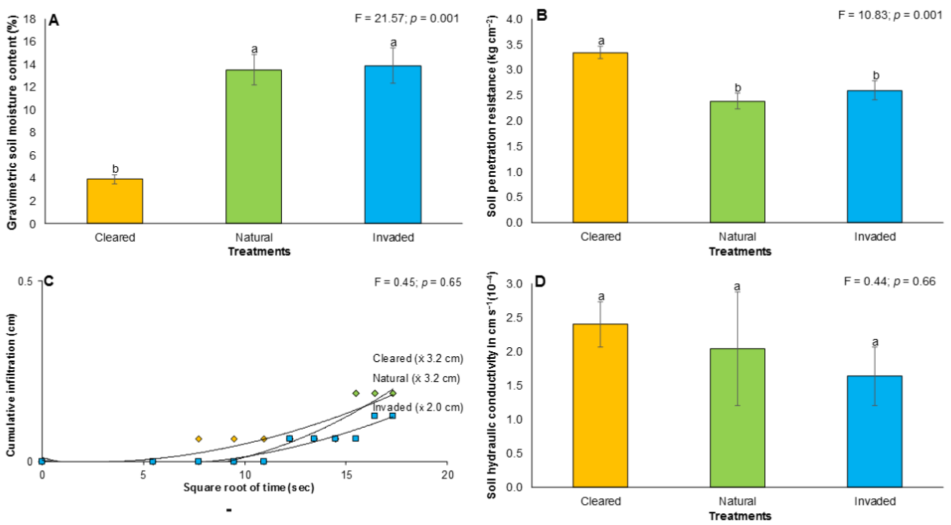

Figure 2. *Results show (A) gravimetric soil moisture content (%), (B) soil penetration resistance levels (C) cumulative infiltration and (D) hydraulic conductivity in soil samples taken from cleared, natural and invaded sites. Bars represent mean ± se and ANOVA results are shown. Bars with different superscripts are significantly different at p < 0.05*

The chi-squared analysis of WDPT classes showed no significant (*P > 0.05*) differences between the three sites (*Fig. 3*). The above-mentioned result is because a greater percentage (80%) of soils in all the three sites were slightly repellent. The remaining 20% in cleared sites were strongly repellent, whereas in the natural and invaded sites the remaining 20% of collected soils were wettable (*Fig. 3*).

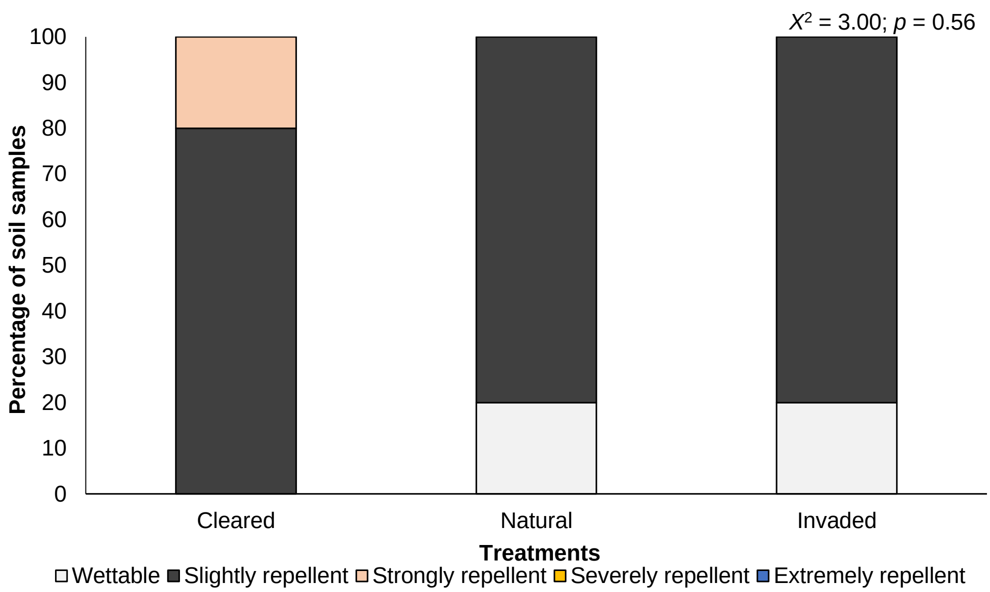

Figure 3. *Distribution of water repellency classes (based on the Water Droplet Penetration Time (WDPT) method) in soil samples taken from cleared, natural and invaded sites. Chi-squared analysis results are shown*

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A total of 42 plant species were identified of which 27 were trees and shrubs, six were herbs and nine were grasses (*Appendix*). Cleared sites recorded a higher occurrences of woody alien invasive plants compared to natural and invaded sites. The most commonly occurring woody invasive alien plants in the cleared sites were *A. mearnsii*, *Lantana camara*, *Psidium guajava*, *Solanum mauritianum*, *Eucalyptus spp.* and *Rubus rigidus*. Species richness showed significant ($P < 0.001$) differences between all the three sites (*Table 3*). Higher species richness was recorded in cleared sites compared to natural and invaded sites. Comparisons on species richness per growth form showed significant ($P < 0.05$) differences between all three sites for all the growth forms (*Table 3*). Trees, shrubs and herbs were higher in cleared and natural sites compared to invaded sites, whereas grasses were higher in cleared sites than in natural and invaded sites. Both Shannon-Wiener and Simpson's index of diversity were significantly ($P < 0.01$) higher in cleared and natural sites compared to invaded sites (*Table 3*). Evenness index showed no significant ($P > 0.05$) differences between all the three sites.

Table 3. *Comparison of indices of diversity between cleared, natural and invaded sites. Data are means ± se and One-ANOVA results are shown*

	Cleared	**Natural**	**Invaded**	**One-way ANOVA**	
				F - values	***P* - values**
Species Richness	23.20 ± 1.83^a	16.20 ± 1.83^b	10.20 ± 1.02^b	16.45	0.001
Shannon-Wiener	2.40 ± 0.07^a	2.29 ± 0.12^a	1.71 ± 0.17^b	12.14	0.001
Simpson's index of diversity	0.87 ± 0.01^a	0.87 ± 0.02^a	0.75 ± 0.03^b	10.37	0.002
Evenness index	0.77 ± 0.02^a	0.83 ± 0.02^a	0.74 ± 0.03^a	3.73	0.06
Species richness per growth form					
Richness of trees and shrubs	12.20 ± 1.16^a	9.20 ± 0.80^a	6.40 ± 0.75^b	9.94	0.003
Richness of herbs	5.00 ± 0.89^a	4.20 ± 0.37^a	2.40 ± 0.25^b	5.32	0.02
Richness of grasses	6.00 ± 1.05^a	2.80 ± 0.74^b	1.40 ± 0.25^b	9.82	0.003

Discussion

The removal of *A. mearnsii* has triggered varied changes in soil physical properties, decreased soil moisture content, increased soil compaction, and intensifying soil water repellency. Soils underneath both *A. mearnsii* and natural areas exhibited higher soil moisture content compared to soils were *A. mearnsii* was removed. The above findings agree with previous findings by Ruwanza et al. (2013b) who showed that soils in cleared areas have lower moisture content than soils in natural and invaded areas, though the above study was conducted in *Eucalyptus* cleared sites. The reasons for higher soil moisture content underneath natural and *A. mearnsii* invaded areas could be linked to higher stand densities compared to the cleared areas. Generally, soils underneath vegetated areas have higher water holding capacity than soils in areas where vegetation has been removed (Wang et al., 2013; Schoonover and Crim, 2015). High water holding capacity in vegetated areas could be a result of hydraulic redistribution, thus the transportation of water via plant roots from wet to drier parts of the soil profile (Leffler et al., 2005). Orwa et al. (2009) indicated that *A. mearnsii* develop a superficial lateral root system whose taproot development is largely depends upon the depth of the soil, thus allowing the plant access to water from the water table. Besides hydraulic redistribution as a factor contributing to the observed soil moisture content differences

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between sites, increased litter content cover underneath both natural and invaded areas could explain the higher soil moisture under these areas compared to cleared areas. Litter is known to provide soil cover, which facilitates the capture of rainwater and avoid evaporation (Dormaar and Carefoot, 1996). Besides, the canopy of both natural and *Acacia* species has the potential to provide shelter for soil moisture thus making it high upon being captured by litter (Mugunga and Mugumo, 2013).

The removal of *A. mearnsii* is expected to cause soils to become less repellent given that some studies have shown that invasion by *A. mearnsii* causes soils to be repellent (Ruwanza, 2017). Contrary, results of this study showed that soils in cleared areas were strongly repellent with the bulk being slightly repellent. The reason why some soils in the cleared areas were strongly repellent compared to the natural and invaded areas could be linked to reduced soil moisture content and soil compaction that was reported in the cleared areas. Soil with low moisture content, which are generally compact, are known to be repellent (Diehl, 2013). Soil compaction on cleared areas could be linked to the clearing method used to remove the invasive trees, especially were mechanical harvesting is used. Mechanical harvesting of plants has been found to trigger soil compaction and repellency, which can persist for years after clearing (Titshall et al., 2013).

The removal of alien plants by WfW assumes that natural vegetation will recover unassisted (Esler et al., 2008; Fill et al., 2018). Although results of this study indicate that the clearing of *A. mearnsii* facilitates an increase in native vegetation diversity, the presents of woody invasive alien plants may hinder this recovery process. Previous studies have reported that removal of *Acacias* facilitates native species recovery (Pretorius et al., 2008; Ndou and Ruwanza, 2016; Fill et al., 2018). However, rapid secondary invasion by invasion alien grasses and herbs was observed in all the above-mentioned studies. However, this study observed the dominance of woody invasive alien plants in cleared areas. The reason for the dominance of these recruiting woody invasives could be that the removal of *Acacias* facilitated soil stored seed bank of other invasives to germinate. Also, the clearing of *Acacias* is known to facilitate the recruitment of woody invasive alien plants due to the increased availability of soil nutrient resources (Pretorius et al., 2008). The recruitment of woody invasive alien plants can negatively affect native species recovery and slow down the native vegetation recovery process. This is because the fast-growing recruiting woody invasive alien plants have the potential to outcompete recruiting native species for resources (e.g. soil nutrients) thus negatively affecting the recovery process.

Conclusions and recommendations

Although native vegetation recovery is improving in cleared sites, it can be slowed down by the recruitment of secondary woody invasive alien plants. The above results point to the need for effective follow-up and monitoring of cleared areas so that recruiting secondary invaders are removed. Effective monitoring may include increasing the follow-up interval to facilitate continues removal of any recruiting invasive plants. Besides, removing recruiting invasive alien plants during follow-up, effective monitoring should include developing appropriate interventions to improve both soil and vegetation recovery. Such interventions during follow-up can include, soil nutrient manipulation and native plant species introduction in cleared areas. However, the efficacy of these interventions will need to be tested.

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Our comparison of cleared, invaded and natural sites has revealed some changes in measured soil and vegetation variables. However, the study results cannot infer that the observed changes were a result of clearing alone, since knowldge on pre-invasion and pre-clearing condition is limited. Given that previous studies have showed that *A. mearnsii* invasion trigger changes in soil properties and vegetation diversity (see Le Maitre et al., 2011; van der Waal et al., 2012), the reported changes in soil and vegetation diversity in this study's cleared sites can be a consequence of *A. mearnsii* removal. The above explanation is further supported by the fact that plant composition in invaded and natural sites were significantly different, this pointing to the notion that invasion cause changes to plant composition, so does removal of the invader in this case *A. mearnsii* (Kumschick et al., 2015; Guido and Pillar, 2017).

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APPENDIX

Appendix 1. *Forty-two frequently occurring species in relation to invasion condition and sites. Values indicate calculated species occupancy frequencies (as a %)*

	Cleared sites		Natural sites		Invaded sites	
Plant name	**Site one**	**Site two**	**Site one**	**Site two**	**Site one**	**Site two**
Trees and shrubs						
Brachylaena discolor	40	40	40	20	10	10
Conostomium natalense	35	5	30	10	0	0
Rhus pentheri	20	0	15	45	0	0

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	Cleared sites		Natural sites		Invaded sites	
Plant name	**Site one**	**Site two**	**Site one**	**Site two**	**Site one**	**Site two**
Nuxia floribunda	20	60	0	20	0	0
Vernonia spp.	0	80	5	15	0	0
Carissa edulis	15	45	50	10	0	0
Lantana camara	45	65	0	0	40	40
Caesalpinia decapetala	60	0	0	80	35	25
Acacia mearnsii	5	80	0	0	40	60
Eucalyptus spp.	55	25	0	0	0	0
Athrixia phylicoides	70	10	10	10	0	0
Asparagus spp.	15	5	5	15	0	0
Vachellia karroo	20	40	50	10	0	0
Psidium guajava	20	20	0	0	0	0
Landolphia kirkii	15	5	0	0	0	0
Euclea natalensis	0	40	10	50	10	30
Lippia javanica	30	30	20	40	0	0
Combretum kraussii	5	15	30	30	0	0
Ziziphus mucronata	30	10	0	0	0	0
Zanthoxylum capense	0	0	30	50	20	20
Nerium oleander	0	0	10	30	0	0
Asparagus falcatus	5	35	20	60	5	15
Diospyros lycioides	0	0	30	10	0	0
Jacaranda spp.	15	25	0	0	10	30
Dombeya rotundifolia	10	10	40	0	15	5
Solanum mauritianum	5	55	0	0	20	60
Rubus rigidus	30	30	0	0	10	10
Herbs						
Bidens pilosa	45	15	0	0	0	0
Felicia sp.	10	30	20	40	5	15
Dicoma anomala	15	5	5	15	20	0
Tylophora sp.	30	10	0	40	0	0
Vernonia natalensis	60	0	5	15	0	0
Ipomoea sp.	20	0	0	0	5	15
Grasses						
Panicum maximum	35	45	20	20	20	60
Cyperus spp.	0	40	0	0	0	0
Setaria sphacelata	20	40	10	10	0	0
Urochloa spp.	5	15	0	0	0	0
Cyperus rotundus	30	10	20	40	25	15
Cynadon dactylon	60	40	5	15	0	0
Themeda triandra	40	0	20	0	0	0
Eragrostis spp.	0	0	0	20	0	0
Aristida transvaalensis	0	20	0	0	0	0

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