Changes in vegetation over nine years after rehabilitating a linear feature in Australia's arid zone

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Abstract. A 36-km road built in 1961 between Ayers Rock (Uluru) and the Olgas (Kata Tjuta), Northern Territory, Australia had seriously deteriorated by the 1980s. A newly aligned road, which was ecologically located and avoid sensitive Aboriginal sites, was completed early in 1991. The old road was rehabilitated by deep ripping, filling with imported sand and topsoil and by grading logs and windrows[1] over the new surface. This paper reports on the effectiveness of the rehabilitation technique used in reinstating vegetation over 8 years and considers whether this rehabilitation aim was met. Plant colonisation and succession were monitored on 15 paired plots, one in the rehabilitated road and the other in the adjacent undisturbed habitat (with four exceptions) and also on the windrows. Sites at eight creek crossings and those subject to fire and rabbit activity were also monitored. Different landscape units responded in different ways to the rehabilitation. Herbaceous species from imported sand plain fill and top soil eventually dominated the road where they were introduced and were likely to persist in most areas because of local recruitment. The revegetation of the road has stabilised the old road surface as observed by the reduced erosion although succession did not always approach the reference site communities because of a greater resemblance to the Simpson Land System. Over the 8 years of monitoring considerable changes in vegetation occurred and are probably continuing. Only the road sites in the Simpson Land System approached the condition of the adjacent undisturbed vegetation because the vegetation of the other two land systems became closer to that of the Simpson Land System rather than to that of the surrounding vegetation. It is recommended that the introduced Buffel grass, known to alter landscape-level processes by reducing native herbaceous species and increasing risk of high intensity wildfire, which is most evident at creek crossings, should be controlled. Recommendations are made for improved management.

Additional keywords: Karee Land System, Killen Land System, plant density, plant succession, old road, Simpson Land System.

Introduction

Long-term monitoring is vital in order to understand responses of vegetation structure and ecological processes over temporal and spatial scales in natural environments (Tongway and Ludwig 2007). These types of studies are particularly relevant to vegetation rehabilitation efforts but little, if any, long-term monitoring has been carried out in Australia (Thompson and Thompson 2004; Clarke *et al*. 2005). Although rehabilitation practices and management have increased in number over the last few decades (McDonald and Williams 2009; Christian-Smith and Merenlender 2010; Suding 2011), most work in Australia has been associated with restoring mined sites or riparian zones (Norman *et al*. 2006; Grant and Koch 2007). Arid-zone restoration is particularly problematical because of variable rainfall (Allen 1995) and seeding is a problem because of removal by seed-harvesting ants (DeFalco *et al*. 2009). No attempts have been yet documented in Australia of revegetation of a linear feature, such as a road, in the arid zone.

Impacts on the native arid-zone vegetation recorded over the last 200 years since European settlement include variable weather regimes, increased incident and extent of fire, grazing, invasive species and mining (Cohen 1990; Bowman 1998; Sinclair 2005; Stafford Smith *et al*. 2007). The most benign being fire as soil surface is little disturbed and the seed bank can survive (Wijayratne and Pyke 2012). It is well documented that grazing of hard-hoofed stock not only damages the actual vegetation but also breaks up the fragile cryptogamic crust essential for sustainable ecosystem function (Dunne 1989). The damage from feral vertebrates, such as the rabbit, has also been well documented (Moseby *et al*. 2009) but the impact of invasive weeds, such as Buffel grass, now increasing its range, has only recently been reported (Clarke *et al*. 2005; Smyth *et. al.* 2009; Miller *et al*. 2010). Revegetation in the arid zone is difficult to achieve partly because of the low, sporadic and unpredictable annual rainfall. Rehabilitation of a lengthy, heavily used road requires techniques not before attempted.

The closure and rehabilitation of the 36 km of degraded main road in Australia's so-called arid 'Red Centre' between Ayers Rock (Uluru) and the Olgas (Kata Tjuta) in 1991 provides an example of revegetation of a linear feature in an arid zone. It was an important step towards the ecological and cultural protection of the unique landscape surrounding these two iconic and highly visited features of the Uluru-Kata Tjuta National Park and World Heritage Area (Fig. 1). The road had been constructed in 1961 and had seriously deteriorated by the 1980s because of increased traffic, grading, unsuitable alignment and occasional flooding. Sunken sections of road were capturing runoff from Kata Tjuta and adjacent sand dunes, re-directing the natural runoff pattern and washing away topsoil from the road with each rainfall event (Griffin and Nelson 1989).

An independent report recommended that the old road be decommissioned and rehabilitation works be conducted within the year of road closure in 1991 with the aim of stabilising the road surface and revegetating it to be ecologically sustainable, and returning it to as close to the condition of the surrounding undisturbed vegetation as possible (Griffin and Nelson 1989). The recommendations were carried out by early 1992. To assess whether the recommended rehabilitation techniques achieved the goals set, quantitative vegetation and visual erosion monitoring were carried out along the old road at regular intervals after rehabilitation to identify (2) the changes in plant density and floristic composition following the rehabilitation, (1) the areas of erosion, and (3) the locations of introduced (weed) plant species. This paper assesses the effectiveness of the rehabilitation techniques in meeting the rehabilitation aims used on the Old Kata Tjuta Road over 8 years from 1992 to 1999.

Sites

The Old Kata Tjuta Road extends west from near the present Uluru Entry Station to Kata Tjuta for ~36 km and traverses three land systems, the Gillen, Karee and Simpson (Fig. 1*a, b*). It traverses six major (3b, 3c, 3d, 3e, 4a and 4b) and three minor land units (5f1, 5f2 and 5a2) (Allan 1984) within the major systems (Saxon 1984).

The Gillen Land System covers the Uluru and Kata Tjuta monoliths (high ridges and mountain ranges), foothills, fans and alluvial fans and plains with some watercourses. It comprises rugged sandstone and alluvial soil types. Vegetation cover is sandy open woodland and mulga. The Karee Land System covers gently sloping plains, low dunes together with mulga drainage depressions and is of much more uniform topography than the Gillen Land System.

The Simpson Land System includes sand plains and dune fields that occur within Uluru-Kata Tjuta National Park (Table 1). Hummock grasslands with *Triodia pungens* (Soft Spinifex) dominate the dune slopes, and shrubs dominate the dune crests. *Acacia aneura* (Mulga) and perennial grasses occur on the red earth swales (Fig. 2), and *T. pungens* with occasional *Allocasuarina* sp. (Desert Oak) occurs on the red earthy sand swales (Allan 1984). Minor vegetation assemblages are found on rocky outcrops, in creeks and gorges, and around salt lakes (Allan 1984). All creek crossings sampled were within drainage lines of Land Unit 3b. The botanical names used follow the Australian Plant Names Index (2012).

At Uluru, average annual rainfall from 1987 to 2000 (14 years) was 332 mm. Months of highest rainfall were from January to March, and the lowest in July and August, indicating a predominately semiarid climate (Australian Bureau of Meteorology 2010). Rainfall data used in analyses were obtained from the Yulara meteorological station (1987–91), and from the Uluru weather monitoring station (1992–99). Examination of the rainfall records for two monitoring stations has shown that, although sometimes large short-term differences occur, in the long term, rainfall at Yulara and Uluru are usually of similar magnitude. During the period of fieldwork, annual rainfall averaged ~200 mm with very low rainfall in 1996. Months of highest rainfall were from the end of February to March, and from the end of November and December.

Rehabilitation treatment

Rehabilitation of the road involved first ripping, mainly longitudinally along the road surface, but if slope was excessive, a sinuating pattern of rips were made (Fig. 3). The depressions were filled with imported sand from the Simpson Land System, (Land Unit 5d1, Allan 1984; Fig. 4). Ripping has been shown to be beneficial in restoring infiltration capacity (Luce 1997). Finally the windrows were scalped of top soil from the edge of the road and the material graded over the road into the centre so that the surface was re-contoured to relate to the surrounding environment. A single trial site (site 23), was established in September 1992 along a 200–300 m stretch of road with brush to provide cover.

On long slopes, diversion banks were cut diagonally across the rehabilitated road every 200–300 m to force water into adjacent land units where the slope was 3% or more. These diversion banks were constructed over the whole 35 km of the road and their position was determined by slope. No maintenance has been carried out on the road since then and traffic has been minimal and restricted to the occasional maintenance and indigenous vehicle (Fig. 5).

Monitoring methods

Seven sites for monitoring were located within the Simpson Land System, four in the Karee Land System and four in the Gillen Land System (Tables 1 and 2) with an additional eight unpaired sites at creek crossings in the Gillen System. Sites were selected using air photo interpretation in conjunction with land unit and vegetation community maps and ground truthing (Low and Foster 1992). Care was taken to locate sites within the six major (3b, 3c, 3d, 3e, 4a, 4b) and three minor (5f1, 5f2, 5a2) land units (Fig. 1). Ruiz-Jaen and Aide (2005) note that at least two reference sites should be established. In this project at least four and maximum six sites were located on each of three land systems. At each site, paired plots (sub-sites) were chosen, with one plot of each pair located

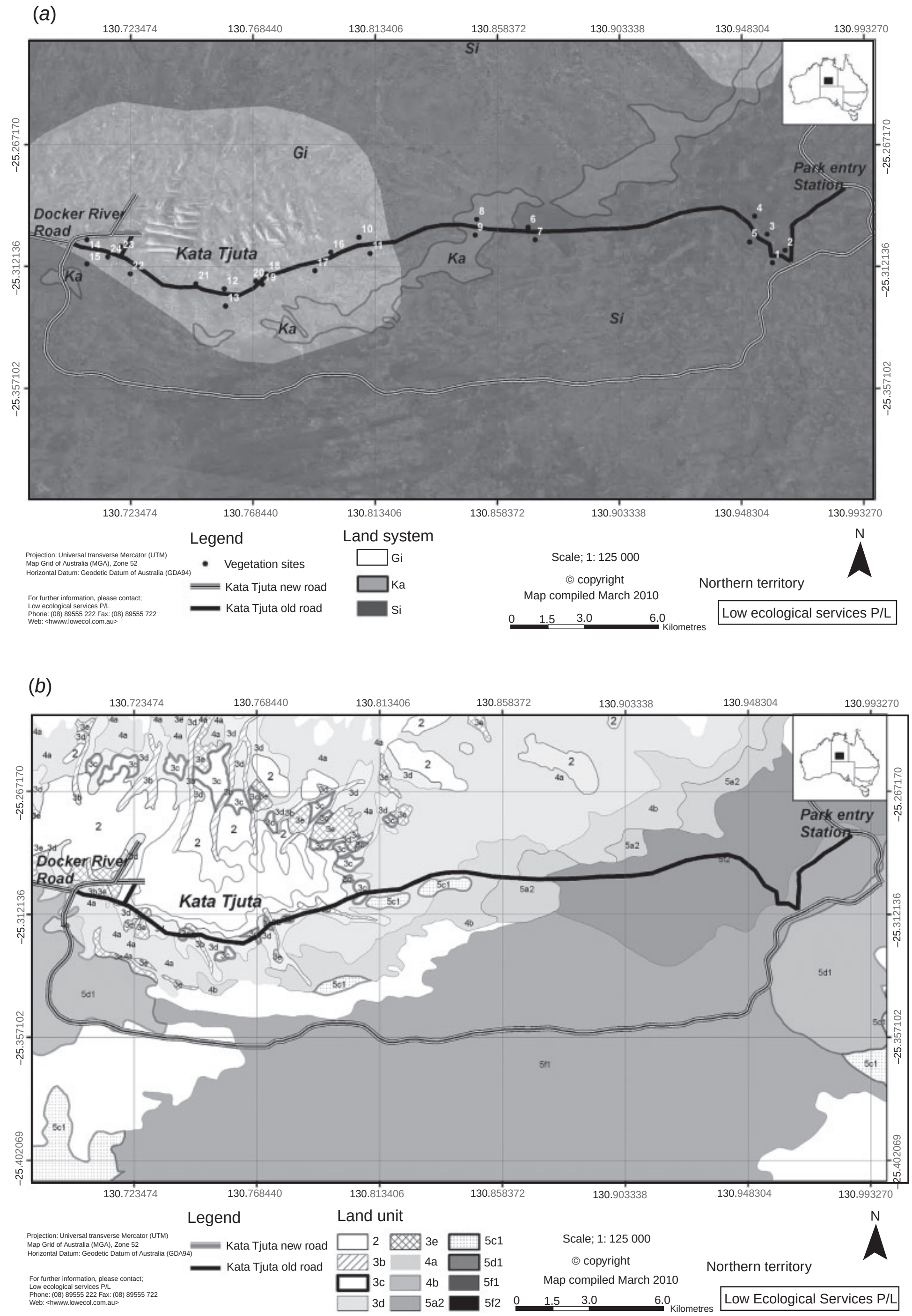

Fig. 1. (*a*) Map showing new and old routes of the Kata Tjata roads andland systems (Gi, Gillen; Ka, Karee; and Si, Simpson) and (*b*) map showing land units (2, annual grassland/some low trees and shrubs, 3b, sparse bloodwood/mixed shrubs and perennial grasses, 3c, annual grasses/very sparse shrub cover, 3d, scattered bloodwood and mulga over perennial grasses, 3e, open annual short grasses/scattered mulga or corkwood and variable shrub cover., 4a, dense mulga groves/sparse perennial grass understorey and annual short grass intergrove, 4b, clumped or scattered mulga, 5a1, hummock grassland dominated by soft spinifex/scattered shrub and desert oaks, 5a2, hummock grassland dominated by hard spinifex/scattered shrub and desert oaks, 5b1, open mallee scrub/sparse soft spinifex understorey, 5c1, open woodland/desert oaks with hard spinifex/shrubs on dune crests, 5d1, hummock grassland dominated by soft spinifex/shrubs on crests/mulga and perennial grasses on red earth swales,, 5f1, hummock grassland dominated by hard spinifex on dunes/dense mulga on red earth swales, 5f2, hummock grassland dominated by soft spinifex on dunes/dense mulga on red earth swales).

Table 1. Paired sites sampled, listed according to land system and land unit with a description of each land unit

Sites for comparison	Land system	Land unit	Description of land unit (Allan 1984)
1 and 2	Simpson	5f1 (minor)	A parallel dune system of short aligned ridges and long linear swales of medium-textured red earths or red earthy sands. Hummock grasslands with soft spinifex (*Triodia pungens*) dominate the dune slopes and mulga is restricted to red earth swales
3, 4 and 5	Simpson	5f2 (minor)	A parallel dune system of short aligned ridges and long linear swales of medium-textured red earths or red earthy sands. Hummock grasslands with hard spinifex (*Triodia basedowii*) dominate the dune slopes and mulga is restricted to red earth swales. Three sites were located here to compare vegetation recovery post-fire (5) and following road rehabilitation (3) with the natural undisturbed site (4)
6 and 7	Simpson	5f2 (minor)/ 5a2 (minor)	Sites in mallee shrubland on a transitional area of sand plain between upland systems and the dune fields. Hummock grasslands dominated by hard spinifex (*T. basedowii*). Scattered shrubs and desert oaks occur. Combined with the above
8 and 9	Karee	4b (major)	Gently sloping plains with sandy loam soils down slope of unit 4a. Clumped or scattered mulga over perennial and annual grasses
10 and 11	Gillen	3c (major)	Sites on calcareous interfluves between drainage lines in fans and alluvium radiating from Kata-Tjuta. Annual grasses with very sparse shrub cover
12 and 13	Gillen	3d (major)	Sites on sandy interfluves between drainage lines in fans and alluvium radiating from Kata-Tjuta. Scattered Bloodwoods and Witchetty Bush over perennial grasses
14 and 15	Karee	4a (major)	Gently sloping plains with clayey loam soils fringing the fans and alluvium areas. Contour-aligned groves of dense mulga with a sparse perennial grass understorey and annual short grass intergrove vegetation

Fig. 2. The creation of a ‘Triodia road” is clearly delineated as the road passes through an *Acacia aneura* community. The access track at right follows the windrows.

Fig. 4. Natural vegetation surrounding the source material of the road fill. This Fig. shows a soft spinifex community dominated by *Triodia pungens*, with *Grevillea juncifolia* in the foreground and *Allocasuarina decaisneana* and *Aluta maisonneuvii* to the left.

Fig. 3. The sand quarry where the fill for the rehabilitation of the road was sourced. Notice the depth of the soil removed (over 1 metre). Some road areas may have been filled with soil from this depth, hence the poor growth results for some areas.

Fig. 5. Site 6A and B in 1992 (Simpson Land System). Initial revegetation in this sandy land unit where road fill is similar to adjacent soils is progressing well.

Table 2. Paired rehabilitated road, naturally disturbed and reference sites sampled, listed by land system

Land system	Rehabilitated road sites		Natural vegetation sites	
	Road bed	Road windrow	Naturally disturbed	Natural undisturbed vegetation (reference)
Simpson	1A	1B	2a (naturally burnt)	2b (partly burnt)
	1C	1D	–	2c
	3A	3B	5a (naturally burnt)	4a
	3C	3D	5b (partly burnt)	4b
	6A	6B	7a (naturally burnt)	–
	6C	6D	–	7b
Karee	8A	8B	–	9a
	8C	8D	–	9b
	14A	14B	–	15a
	14C	14D	–	15b
Gillen	10A	10B	11a (rabbit warren)	–
	10C	10D	11b (rabbit warren)	–
	12A	12B	–	13a
	12C	12D	–	13b
	23A (brush cover), 23B (no brush)	–	–	–

on the rehabilitated roadway and the other, a reference site, located 20–50 m away from the road in the adjacent native vegetation. On the roadway, both the road and windrow were sampled. In six cases, in the adjacent native vegetation, sites disturbed by fire or rabbits were also sampled (Tables 1 and 2). No true controls were possible because of management requirements to restore the whole length of the road. Each monitoring site was 25×200 m. Twenty-five quadrats of 1 m^2 each, selected at random by a quadrat throw at every 10 m were used at each sub-site to estimate herbage mass, cover, species composition and frequency. The exception was at sub-site 1c in 1994, where 24 quadrats were used. In 1992, floristic composition and cover, seedling and tree presence and abundance were measured on the 15 sites and all sites were photographed. In order to compare the rate of revegetation between naturally disturbed areas and artificially disturbed areas, some sites were included that had been burnt (sites 5, 5b, 2a, 2b, 7) and others where rabbit disturbance was evident (sites 11a and 11b) (Table 2). Site 5 was located in a naturally burnt area of a mulga/sand plain community although sub-site 5b was only partially burnt. Wildfire burnt the reference sites sub sites 2a, 2b (partially burnt) and 7a after selection. A further eight unpaired, reconstructed creek crossing sites in (3b) of the Gillen Land System were selected in 1992 where soil erosion was assessed by aerial photographic interpretation and recovery in vegetation measured by eye (Table 3).

The measurements noted above were carried out on six dates; August–September 1992, December 1993, October–November 1994, October 1995, November 1997 and October–November 1999. Standard field survey techniques were used (McDonald *et al.* 1984). Both numbers of species per quadrat and the density of each species were recorded in the 25 quadrats per sub-site. The sub-sites were located along defined permanent transects and stratified in that the road verge, the margin and centre of the road was all sampled to minimise variation. The density of juvenile woody plants was determined from the total number of each species present in a 2000×2-m belt transect within each site. The

Table 3. Unpaired reconstructed creek crossings (drainage lines) listed by land system, land unit and ground type

Unpaired sites	Rehabilitation type	Land system	Land unit
16	Earthen	Gillen	3b
17	Rocky	Gillen	3b
18	Rocky	Gillen	3b
19	Rocky	Gillen	3b
20	Earthen	Gillen	3b
21	Rocky	Gillen	3b
22	Bedrock	Gillen	3b
24	Earthen	Gillen/Karee	3b/4a

per cent foliage cover of mature trees and shrubs was measured using the Bitterlich gauge (Bastin 1989). Total biomass and proportional composition of the herbage were quantified using a Dry Weight Rank estimate (Griffin *et al.* 1997). Photographs of all 23 sites were taken from marked photo points (usually 4) per sub-site.

Creek crossings were selected for photographic monitoring and for observation of species succession through time post-rehabilitation in 1992, 1994, 1995, 1997 and 1999 but the number of quadrats employed varied between years and sites. At sites 16 and 17, additional data was collected from the undisturbed creek bed upstream from the disturbance.

Standard statistical techniques were used to display and interpret vegetation changes both through time and in relation to environmental variables. Multivariate analysis using PATN version 2.3.1 (www.patn.com.au/, accessed 19 November 2011) was employed for classification and correlation of per cent composition of the herbage data and for comparison analysis of the density of juvenile tree and shrub species. Canoco 3.1 was used for the ordinations while S-plus 5 was employed to display the results of Canoco analysis. Ordination of the data through Canoco was an indirect gradient analysis by the unimodal detrended method with the data untransformed. Ordinations are presented as scatterplots. On these scatterplots, sites that appear near each other are similar in species composition. The further apart sites are, the more dissimilar they are in species composition in that year. If a species name appears close to a site label, then the site is dominant in that species. The points for each year have been joined to provide a trajectory as a visual aid to following the change over time for that site. Correlation between the sub-sites and extrinsic variables, based on the ordination analysis (through PATN), was designed to reveal relationships between variables as well as indicate the degree of influence each variable had on the composition of each sample. For the purposes of this analysis, a correlation result of 0.6 or higher revealed a strong influence on the composition of a sample by the environmental variable.

Results

Vegetation responses to the restoration treatment are presented under headings that describe the different plant variables measured. They comprise herbage mass, ordination of composition, abundance of seedling emergence, juvenile tree and shrub density, abundance of overstorey, significant correlations and comments on reconstructed creek crossings and effect of brush cover. All variables showed a positive response over time of monitoring apart from brush cover as described in more detail below.

Photographs of sites in different years after restoration are shown in Figs 2, 5–21. Over the 8 years, herbage mass on all restored road, windrow and reference sites showed a similar gradual increase except for the reference site on the Karee Land System, which was almost stable (Hill *et al*. 2002) and the Simpson System 1A where the increase was considerably more rapid.

Succession is illustrated by the ordinations using vegetation data for all sampling periods for sites 1–15, which are shown in Figs 23–29. The most significant changes shown by the ordinations are noted below.

Grasses and herbaceous plants

In the Simpson Land System, trends for sites 1 as well as 2, although variable, cluster with *T. pungens* by 1999 with burnt sites (sub-sites 2A, 2B) showing the closest affiliation with this species. By 1997, *T. pungens* and *Eragrostis eriopoda* (Woollybutt Grass) were becoming uniform across all sub-sites (Fig. 23). In the same system, on all sub-sites of sites 3, 4, 5, (Figs 14–18, 24) dominant species have changed with *Triodia basedowii* (Hard Spinifex) becoming more dominant though time, although the road sub-site changed from a *Sida fibulifera* (Silver Sida) dominance, in 1992, to *E. eriopoda*, with a *T. pungens* influence in 1999. The dominant species of windrows sub-site 3B were *Sida cardiophylla* and *Rulingia loxophylla* although in 1999 the site was heading towards *E. eriopoda* dominance. The burnt sub-site (sub-site 5A) was similar to the windrows (Fig. 24). On sites 6 and 7, *R. loxophylla* has remained dominant on the windrows throughout monitoring but *T. pungens* replaced *T. basedowii* on the reference site and road (Fig. 25).

In the Karee Land Systems, the road and windrow sites in all years have supported a different species composition compared with the surrounding natural vegetation (i.e. on the reference sites). Pioneer species dominated first followed by *E. eriopoda* by 1999 (sub-sites 8A and 8B) (Fig. 26). The natural vegetation site (sub-site 9A) was variable throughout. There was low variability within sites 14 and 15 in the same system, as points for all years were relatively close together for the road sub-site 14A, with *T. pungens* dominant. Road and windrow sub-sites 14B and 15B rehabilitated independently of each other and of the reference sites as represented by the lines projected in different directions. The species have been determined by the disturbance and fill seed store (Fig. 27).

Within the Gillen Land System, the trajectories of each sub-site 10A, 10B (Figs 8, 9) and 11B were similar, although *Sclerolaena cornishiana* (Cartwheel Burr) dominated the road and windrows, and *Eremophea spinosa* the reference sites in later years (Fig. 28). In the same land system, the road site (sub-site 12A) has clustered closely in the *T. pungens* species space continually, although *T. pungens* comprised less than 10% of windrows. The reference sites (sub-site 13A) and the windrows (sub-site 12B) were similar in that they were variable over time but with *Sclerolaena convexula* (Tall Copper Burr) dominant in 1999 (Fig. 29).

Tree and shrub seedling emergence

Seedling abundance is displayed as total number of individuals counted for individual sites in the Simpson System and for all sites combined in the other two land systems.

The overall pattern shows that three dune species, *Alyogyne pinoniana* (Sand Hibiscus), *Aluta maisonneuvei* (Desert Heath Myrtle) and *Acacia ligulata* (Umbrella Bush), have germinated and persisted along the length of the rehabilitated road throughout the monitoring period (Figs 30, 32). In general, *Acacia aneura* (Mulga) was the most common seedling species on the reference sites except for the sub-site shown in Fig. 29 and *Acacia victoriae* (Acacia Bush) on the road and windrow sub-sites except for the sub-sites shown in Figs 30 and 33. *Acacia ligulata* (Umbrella Bush) seedlings were more common on the road and windrow than on the natural vegetation sites.

On each land system, the dominant seedlings of the natural Simpson Land System (Fig. 30) were always the species that germinated. These were *A. ligulata*, *A. melleodora*, *A. maisonneuvei* and *A. pinoniana*, which persisted on the road throughout, with particular seedling abundance on the reference sub sites, except for *A. ligulata* seedlings, which were highest on the road and windrows (Fig. 30).

In the Gillen Land System, the rehabilitated road has mostly regenerated with the common Gillen Land System species but some Simpson Land System seedlings (*A. maisonneuvei* and *A. pinoniana*) were recorded in the first years. Increased numbers of *A. victoriae* occurred on road and windrows (Fig. 31).

Acacia aneura seedlings were the only ones recorded on all sub-sites in the Karee Land System but rehabilitating sites (windrows and road) were dominated by Simpson Land System species (Fig. 32).

Juvenile tree and shrub density

Reference site 2 of the Simpson System was dominated in 1999 by juvenile *A. maisonneuvi*, *Eremophila wilsii* (Sandhill Native Fuschia) and *Micromyrtus flaviflora* (Yellow Heath Myrtle) although the rehabilitating windrows and road (sites 1W and 1R)

Fig. 6. Site 12A and B (Gillen Land System) 10 months after rehabilitation in 1992. The road remains bare, whilst *Acetosa vesicaria* dominates the verge. Note the relatively poor growth due to being overlain with sub soil.

Fig. 7. The same site (Site 12A and B) in 1999, 8 years after rehabilitation. Note the dominance of the dune field species *Triodia pungens* and *Eragrostis eriopoda*. Also note the relatively poor herbaceous cover at this site due to the use of subsoil fill material.

Fig. 8. Site 10 in 1992, 10 months after rehabilitation (Gillen Land System). The road has revegetated more quickly than Site 12 due to being overlain with topsoil fill. The weed species *Acetosa vesicaria* has colonised the road surface.

Fig. 9. The same site (Site 10) in 1999. This figure. illustrates the dramatic change in species composition and dominance since 1992. The ground cover is becoming similar to adjacent areas. *Acetosa vesicaria* is absent. The site is dominated by dune field species including: *Triodia pungens, Aristida* spp. and *Aluta maisonneuvii*. Once again the growth at this site can be attributed to being overlain with topsoil, not subsoil like Site 12.

Fig. 10. Site 6A and B in 1992 (Simpson Land System). Initial revegetation in this sandy land unit where road fill is similar to adjacent soils is progressing well.

Fig. 11. The same site (10) in 1999, 8 years later. The site has revegetated well and now looks similar to the adjacent vegetation. The successful revegetation of this site with appropriate species is typical of the rehabilitated sites of the Simpson Land System.

Fig. 12. Site 14C and D (Karee Land System) 1992, 10 months after the rehabilitation. Lack of growth due to land fill being sub-soil and local windrow material was insufficient to cover land fill. The windrow has been colonised by pioneer species such as *Salsola kali* and the introduced Ruby Dock**.**

Fig. 13. Site 14C and D eight years after rehabilitation is dominated by dune field species *Triodia pungens* and *Acacia ligulata*. *Alyogyne pinoniana* has germinated and died within the eight-year period. The windrows are comparatively bare, possibly due to scalping during rehabilitation, *Acacia aneura* delineates the surrounds and *Triodia pungens* the road.

have clustered within the dune field species (Fig. 34). The dominant juvenile species present in these rehabilitated areas were *A. melleodora* and *A. pinoniana*. Both road and windrows at site 8 (Karee) are located in a transitional species space in the ordination plot because of dominance by *Acacia murrayana* (Colony Wattle), common in dunefields and other sandy soils (Latz 1995). Only windrows at site 14 (Karee) carried juvenile species representative of the local system (Fig. 33).

This pattern is clearer in the trajectories of juveniles for all sites and for all years in the Simpson System (Figs 34, 35). On sites 1 and 2 the trajectory for the road (site 1R) is away from *A. pinoniana* dominance in 1992 because of the increased density of juvenile *A. melleodora* in 1994 and 1997, and returns to *A. pinoniana* dominance in 1999 as Fig. 34. Although the windrows were dominated by *Senna pleurocarpa* (Fire Bush) in 1992, by 1999 the dominant species of juvenile plants was more

Fig. 14. A mulga swale south of Site 3, 1999, in Simpson Land System. Scalped material from the windrow to recover local top soil to cover the sand plain land fill was insufficient and the windrow area to the left was left unproductive. In contrast to this, the road area to the right has regenerated well.

Fig. 15. Site 5, a control burnt site 10 months after burn in 1992. *Rulingia loxophylla* has abundantly resprouted from rootstock. *Rulingia* also resprouted profusely at many of the scalped windrow sites.

Fig. 16. Site 4, the adjacent unburnt control site, 1992 (Simpson Land System). This site hasn't been burnt for quite a while as evident from the presence of mature spinifex clumps. *Triodia pungens* and *Eragrostis eriopoda* are well established.

Fig. 17. Site 5, burnt control eight years later (refer Fig. 15). *Rulingia loxophylla* has been replaced by *Triodia pungens*. This site is now floristically similar to the adjacent unburnt control site (Site 4).

Fig. 18. Unburnt control site (Site 4) in 1999. Although more established, the vegetation of this site is similar to that of the adjacent burnt control site (refer Fig. 17 above). The site is dominated by *Triodia pungens* with *Acacia aneura* shrubs in the background. *Grevillea juncifolia* has matured and died.

Fig. 19. Site 23A Brush covered site in 1999. This site has remained covered throughout the monitoring period. It has regenerated well.

Fig. 20. Site 23B Brush cover trial site, uncovered site, 1999. Although slower to start, after 8 years of rehabilitation the uncovered site has a similar level of vegetative cover to the covered site (see Fig. 19) and supports a greater species diversity.

Fig. 21. A mulga swale in the the Old Kata Tjuṯa Road in Karee LS 8 years after rehabilitation. The reconstructed surface has held its form quite well. However, revegetation is much slower to respond here due to the sand used as landfill originating from deep within the soil profile.

Fig. 22. Runoff from in front of pond bank on the road south of Kata Tjuta near Site 12 has lead to rilling on the lower end of the pond bank. However, the runoff has been effectively dispersed as sheet flow over the natural plain downstream.

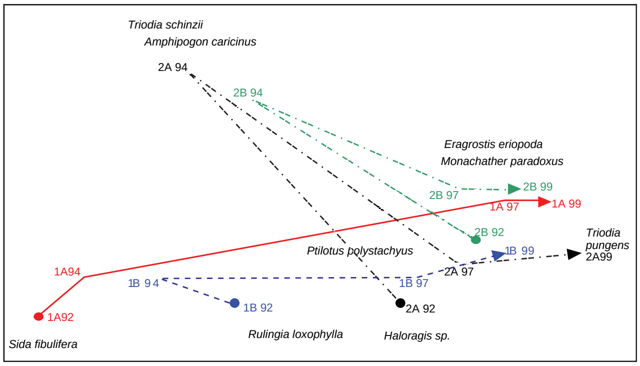

Fig. 23. Ordination of herbage composition for Simpson land system, sites 1 and 2 (1992–1999). Sub-site locations are represented by continuous line for road (1A); dashed line for windrow (1B); dashed and dotted line for natural vegetation (reference sites) (2B (part burnt); and dotted line for burnt natural vegetation (2A). The number represents the year sampled.

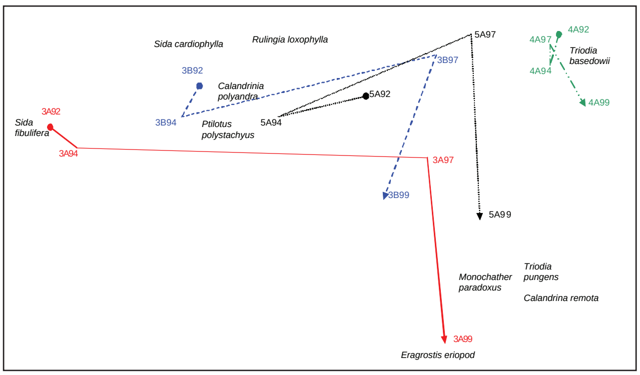

Fig. 24. Ordination of herbage composition for Simpson land system, sites 3, 4 and 5 (1992–99). Sub-site locations are represented by continuous line for road (3A); dashed line for windrow (3B); dashed and dotted line for natural vegetation (4AB); and dotted line for burnt natural vegetation (5A). The number represents the year sampled.

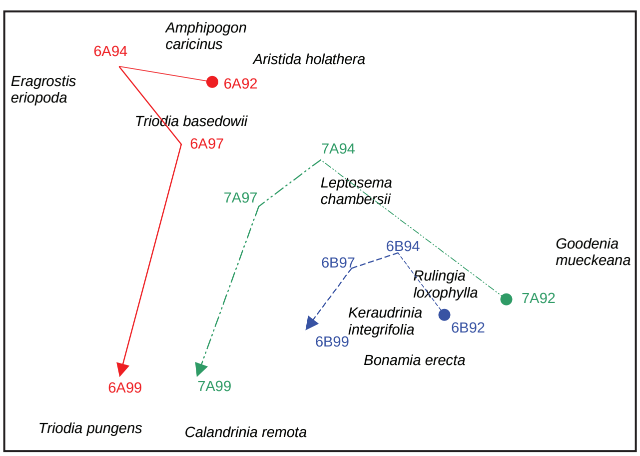

Fig. 25. Ordination of herbage composition for Simpson land system, sites 6 and 7 (1992–1999). Sub-site locations are represented by continuous line for road (6A); dashed line for windrow (6B); and dashed and dotted line for natural vegetation (7A). The number represents the year sampled.

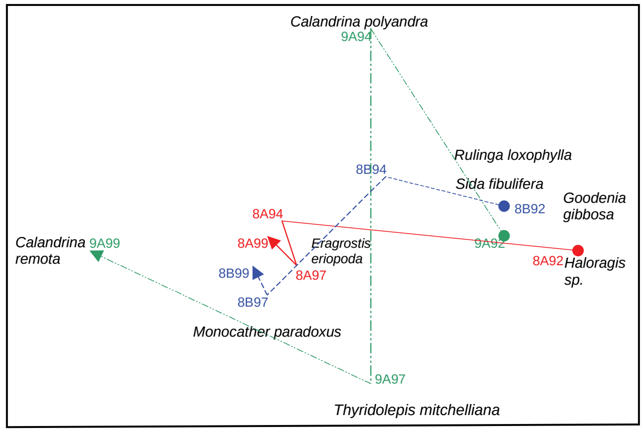

Fig. 26. Ordination of herbage composition for Karee land system, sites 8 and 9 (1992–1999). Sub-site locations are represented by continuous line for road (8A); dashed line for windrow (8B); and dashed and dotted line for natural vegetation (9A). The number represents the year sampled.

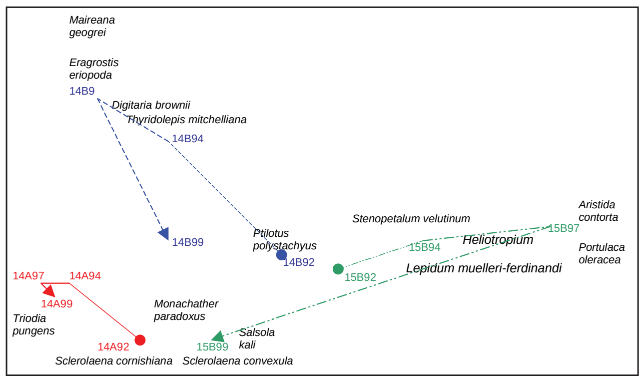

Fig. 27. Ordination of herbage composition for Karee land system, sites 14 and 15 (1992–99). Sub-site locations are represented by continuous line for road (14A); dashed line for windrow (14B); and dashed and dotted line for natural vegetation (15B). The number represents the year sampled.

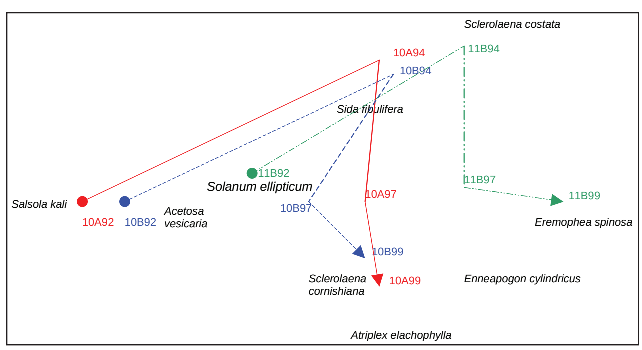

Fig. 28. Ordination of herbage composition for Gillen land system, sites 10 and 11 (1992–99). Sub-site locations are represented by continuous line for road (10A); dashed line for windrow (10B); and dashed and dotted line for natural vegetation (11B). The number represents the year sampled.

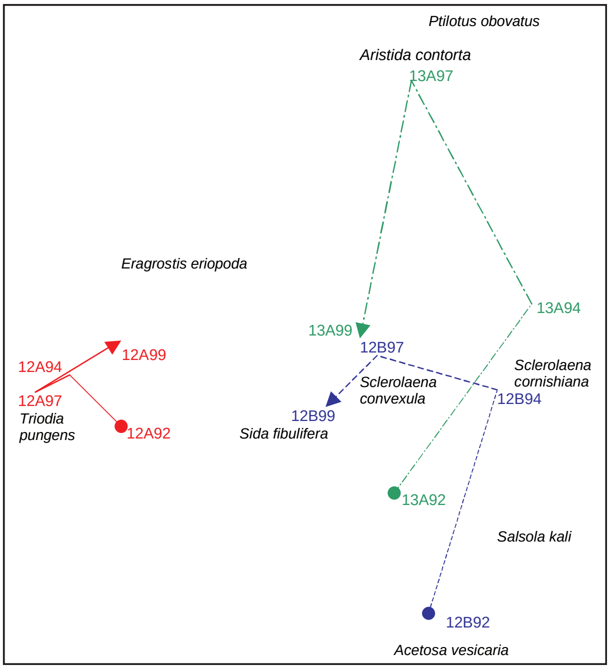

Fig. 29. Ordination of herbage composition for Gillen land system, sites 12 and 13 (1992–1999). Sub-site locations are represented by continuous line for road (12A); dashed line for windrow (12B); and dashed and dotted line for natural vegetation (13A). The number represents the year sampled.

similar to the natural (reference) site 2. There are two reference sites for sites 4 and 5 (Table 2) and both cluster for the first three monitoring occasions (Fig. 35) but by 1999 density of juvenile plants of each site had become dominated by different species resulting in the trajectories moving in opposing directions. Windrow 3W appears in a transitional species space between the reference sites and the road (Fig. 35). By 1999 this trajectory was in harmony with the reference site 5. The road (site 3R) follows an isolated trajectory initially dominated by *S. pleurocarpa* in 1992 influenced largely by *A. melleodora* later (Fig. 35). In 1992 both the road, site 6R, and the windrows, site 6W, recorded juvenile densities distinctly different from the reference sites (7) (Fig. 36). Monitoring in following years indicated that the road and windrows at these localities are revegetating with trees and shrubs that closely approximate the surrounding vegetation (Fig. 36).

In the Gillen Land System, the trajectories of both road sites (sites 10R and 12R) were distinct from the windrows and reference sites, predominately because of dune field species dominance (Fig. 37). The trajectory of road site 10R was heavily influenced by the dune field species *A. pinoniana* in 1992 and 1999 but in intervening years was dominated by *A. victoriae*. The trajectory of reference site 13 remains within a small and isolated area of the ordination plot, indicating a relative stability in the densities of the dominant juvenile tree and shrub species (Fig. 37). Despite interference from rabbits at site 11, the rehabilitated windrows are within a similar juvenile density space as the natural reference site. Distinct differences in the composition of juvenile tree and shrub species densities between

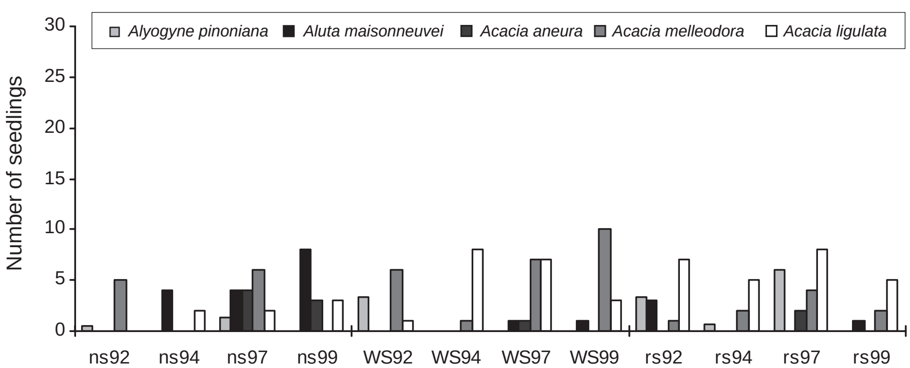

Fig. 30. Tree and shrub seedlings of selected species recorded in the Simpson land system (1992–1999). Sub-sites are represented by the prefixes: ns, natural; ws, windrow; and rs, road. The number represents the year sampled.

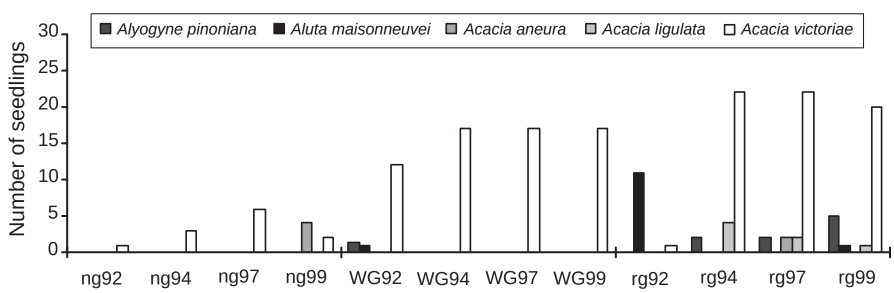

Fig. 31. Tree and shrub seedlings of selected species recorded in the Gillen land system (1992–1999). Sub-sites are represented by the prefixes: ng, natural; wg, windrow; and rg, road. The number represents the year sampled.

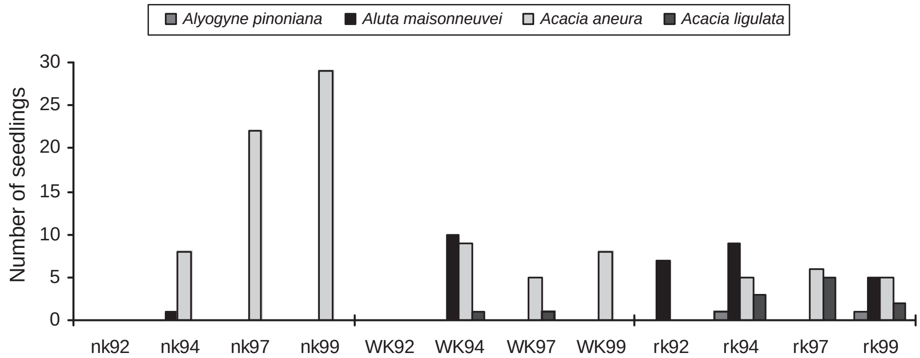

Fig. 32. Tree and shrub seedlings of selected species recorded in the Karee land system (1992–1999). Sub-sites are represented by the prefixes: nk, natural; wk, windrow; and rk, road. The number represents the year sampled.

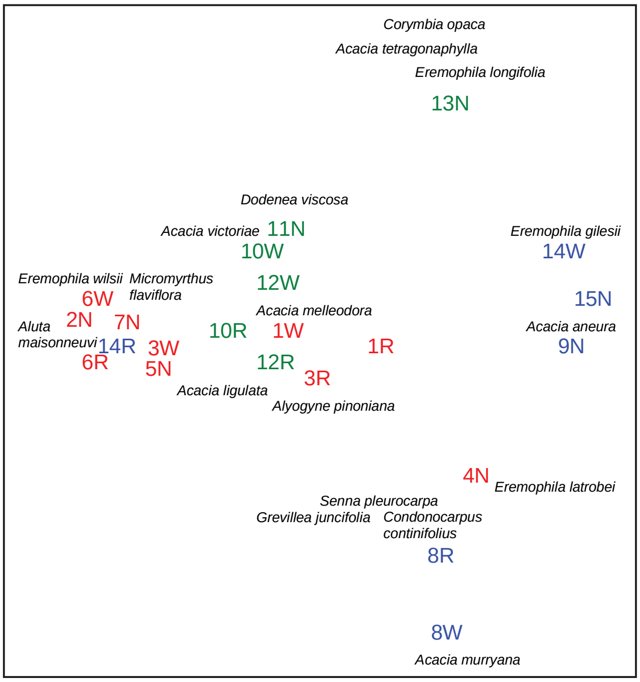

Fig. 33. Ordination of juvenile tree and shrub densities for 1999 for the all sub-sites. Sub-sites are numbered as in Table 1, with R for road, W for windrow and N for undisturbed vegetation.

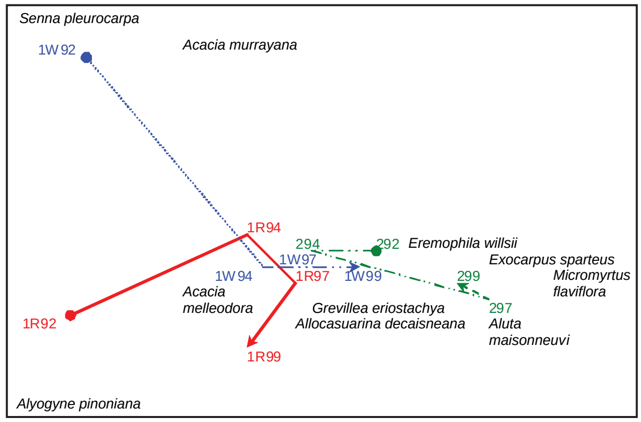

Fig. 34. Ordination of juvenile tree and shrub densities for Simpson land system, sites 1 and 2, (1992–1999). Sub-site locations are represented by continuous line for road (1R); dotted line for windrow (1W); and dashed and dotted line for natural vegetation (2). The number represents the year sampled.

the natural (13), and road (site 12R) monitoring sites has resulted in each site plotting in areas of alluvial or dunefield species dominance, respectively. The windrows site (site 12W) has occupied a transitional area and by 1999 was tending towards the natural replicate of site 13.

Generally, the rehabilitating road and windrow sites of the Karee Land System are divergent from the reference sites, especially for the trajectories of sites 14R and 14W, in the dune field species space in 1999 (Figs 12, 13, 38). Site 14R showed the greatest divergence from the reference sites in juvenile tree and shrub species compared with all other monitored sites. The dominant juvenile species are those of dune fields in contrast to the *A. aneura* dominance of the natural reference site (site 15) (Fig. 38), its (site 14R) trajectory of the site starting and continuing in a different direction to the surrounding vegetation (Fig. 36). The short trajectories of reference sites 9 and 15 are indicative of a relatively stable species composition and dominance. Reference site 15 has short trajectories through the species space being persistently dominated by *A. aneura* and influenced by *Corymbia opaca* (Bloodwood). Although the trajectory of both the road (site 8R) and windrows (site 8W), moved towards the natural replicate in 1994, the results of the remaining monitoring years has been divergent with the road site clearly moving towards dune field species. Although the windrows site, site 14W, is becoming more similar to the reference sites by 1999, it remains in a transitional species space. There were no juvenile tree or shrub species recorded in the windrow sites in 1992.

Correlation analysis

A range of previous rainfall parameters and land forms were found to be positively correlated with the composition of

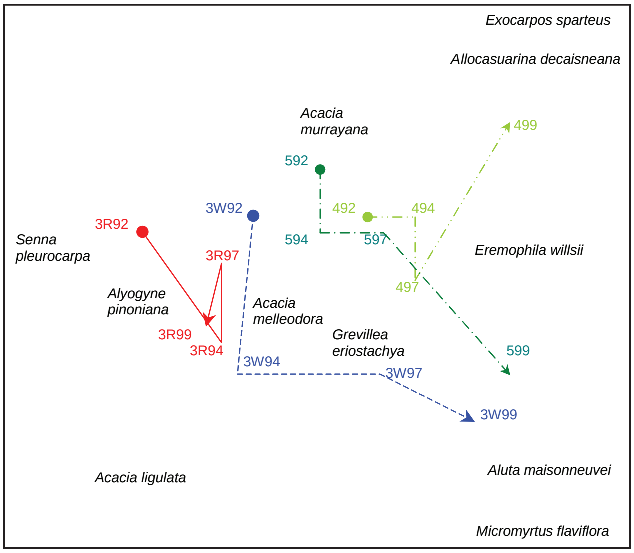

Fig. 35. Ordination of juvenile tree and shrub densities for Simpson land system, sites 3, 4 and 5 (1992–1999). Sub-site locations are represented by continuous line for road (1R); dashed line for windrow (3W); and dashed and dotted line for natural vegetation (4, 5). The number represents the year sampled.

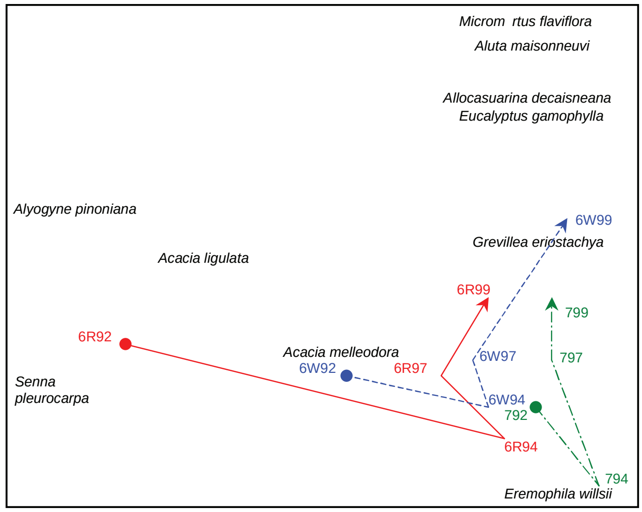

Fig. 36. Ordination of juvenile tree and shrub densities for Simpson land system, sites 6 and 7 (1992–1999). Sub-site locations are represented by continuous line for road (6R); dashed line for windrow (6W); and dashed and dotted line for natural vegetation (7). The number represents the year sampled.

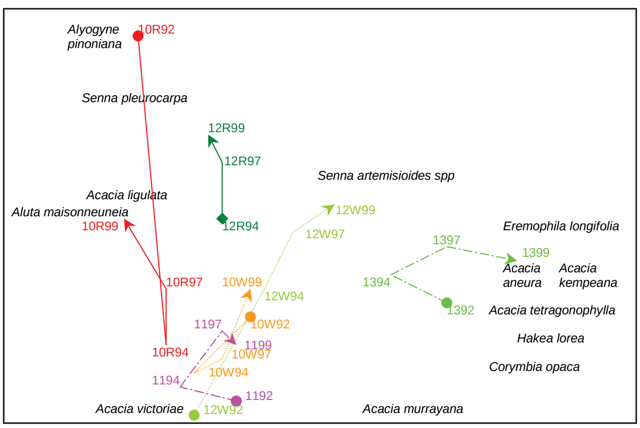

Fig. 37. Ordination of juvenile tree and shrub densities for the Gillen land system (1992–1999). Sub-site locations are represented by continuous line for road (10R and 12R); dotted line for windrow (12W and 10W); and dashed and dotted line for natural vegetation (13 and 11). The number represents the year sampled.

herbaceous species. Some soil attributes, such as topography and pH, were also positively correlated with juvenile shrub emergence on all sites. The strongest correlations were with rainfall over the previous 6–48 months for all monitoring occasions for sites 1–13. For sites 14 and 15, level of disturbance, depth of fill and soil attributes were the most significant. Details of the correlations are given in Hill *et al.* (2002).

Abundance of overstorey

Only two (sites 8 and 12) of the seven road and windrows sites in the Simpson system have developed trees or shrubs with a

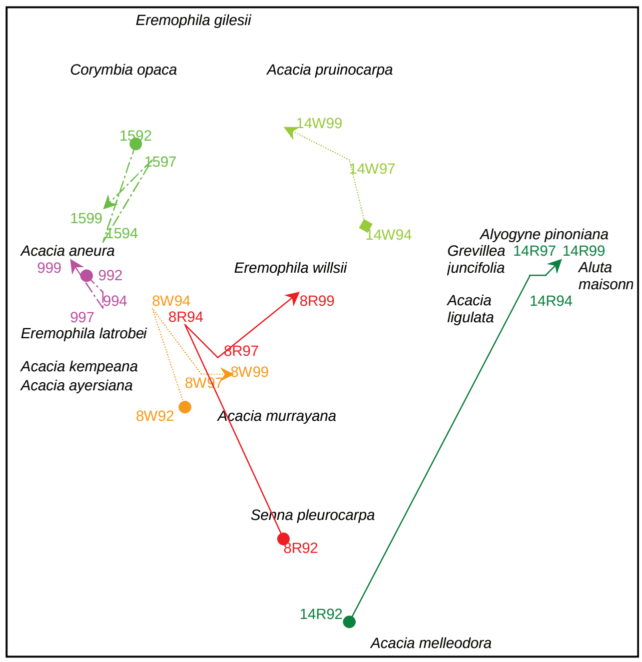

Fig. 38. Ordination of juvenile tree and shrub densities for the Karee land system (1992–1999). Sub-site locations are represented by continuous line for road (8R and 14R); dotted line for windrow (14W and 8W); and dashed and dotted line for natural vegetation (9 and 115). The number represents the year sampled.

sufficient height and canopy width to be measured. However, this type of vegetation was variable from year to year. Species included the classic dune field species, *A. ligulata*, *A. murryana*, *A. pinoniana* and *Senna artemisiodies* subsp. *artemisiodies*

(Silver Cassia). By 1999, only *A. ligulata* had measurable canopy on site 12 (Fig. 7).

Reconstructed creek crossings

For sites 16, 17, 19 and 20, species in the undisturbed area of the creeks tended to be native to the local land system although numbers were fewer than in rehabilitated creeks. *Acacia masionneuvii* was present sporadically as were *Triodia* spp. Perennial tree and shrub seedlings, native to the local system and present in reconstructed areas, were *A. tetragonophylla*, *A. victoriae*, *C. opaca* and *Hakea suberea* (Long Leafed Corkwood). *Cenchrus ciliaris* (Buffel grass) occurred at each site throughout. Up to the 1999 survey, minor erosion in the Karee and Gillen Land Units had been located in a few areas of low vegetative cover and sloping conditions such as creek crossings or diversion banks that were too short to divert runoff water away from the road (Fig. 22). Apart from these few cases, using a subjective assessment of photogrammetry, it is clear that the physical reconstruction of creeks has persisted over the long term. Visual observations indicate that diversion banks have been relatively effective in limiting erosion from the rehabilitated road.

Floristic data showed that sites 18 and 21 were initially dominated by the weed, *Acetosa vesicaria* (Rosy Dock) (53.6 and 63.6% of herbage mass DM, respectively), but by 1999 *Atriplex elacophylla* (Annual Saltbush), was dominant (51.8% of herbage mass DM) on site 18 but was only 25.4% of herbage mass DM on site 21, which is likely to be a natural succession. *Themeda triandra* (Kangaroo Grass) was also present at low densities. The exotic *Cenchrus ciliaris* was present on sites 18 and 21 comprising 5.0% of the DM of the herbaceous layer (1992–97). On the other hand, native grasses, *Themeda triandra* (30.5%), *Panicum decompositum* (Native Millet) (18.9% of herbage mass DM) and *Dactyloctenium radulans* (Button Grass) (47.6% of herbage mass DM) in some years were dominant on site 22.

Brush cover study

In the brush cover study, the uncovered site 23B, although slower to revegetate, had a greater species richness by almost two-thirds than the brush-covered site (23A) by 1999 but, without replication, this result is not indicative of an effect. *Triodia pungens* and *Eragrostis eriopoda* persisted on both sites (Figs 19, 20).

Detailed results for each year of succession are filed at the Uluru-Kata Tjuta National Park office at Uluru and in Canberra at the Department of Environment, Water, Heritage and the Arts, and are available on request.

Discussion

The data presented here show broad-scale trends of increasing plant density and herbage mass over 9 years. It also shows that plant composition is highly variable over time even on some reference sites and that seedlings recorded on windrows and old road sites are generally more similar in composition to each other than to the surrounding vegetation with juvenile trees and shrubs following the same pattern.

In each land system, as might be expected, the road and windrow sites in the Simpson Land System are rehabilitating with similar juvenile tree and shrub species to those found naturally in the Simpson Land System because it was the origin of the imported fill. However, plant succession on the road of the other two land systems was more variable over the whole period. In addition, trajectories of sites on similar land systems were not necessarily similar or always determined by the origin of the soil fill as a positive correlation was found between succession progress and rainfall preceding date of monitoring (Hill *et al*. 2002).

The mechanical method of rehabilitation used here, that did not include seeding or planting, worked well in the Simpson System but not so well for the Gillen and Karee Systems.

The results emphasise the importance of rehabilitating sites with soil sourced from the same land unit especially as it has been shown for the arid zone that vegetation is influenced more by geomorphic strata than by management (Sparrow *et al*. 2003). Holden and Miller (1995) had no success in direct seeding for restoration in the arid zone but considerable success was achieved in this study in the Simpson Land System using the existing soil store of seeds only. As the majority of viable seed is within the top 10 cm for most soil types (Lawrie 1984; Grant and Koch 1997; Simpson 1999), rehabilitation fill would need to be stripped from this stratum from each land unit rather than from any other source. Pragmatic and conservation issues made this unacceptable for Karee and Gillen Systems. As some of the sources of soil originated from depths greater than 10 cm, it is assumed that, in line with the findings of Blomquist and Lyon (1995) when studying sand dunes in Nevada, USA, the topsoil may have contained viable seed.

One problem was that the low frequency of monitoring, together with the variation in seasons of sampling, created challenges for the analysis and interpretation of the data. Another problem was the presence and spread of two introduced species within and adjacent to the rehabilitated road in the Karee and Gillen Land Systems. *Acetosa vesicaria* was the only introduced species that was identified in the Simpson Land System but *C. ciliaris* poses the greatest threat to ecosystems as it can alter the intensity of wildfires by burning more vigorously and for longer than native ground cover species. Fires of *C. ciliaris* can damage the soil's seed bank as well as kill mature trees that would normally be unaffected by fire (Miller *et al*. 2010). Although the current infestation is relatively small, removal of this species is a high priority for the maintenance of the biological significance of Uluru-Kata Tjuta National Park and is of a greater importance to ecosystem conservation than any of the physical rehabilitation discussed or recommended in this paper. Attention should be given to reducing the spread of this weed particularly along drainage lines in wet conditions and by vehicle movements.

Conclusions

The main findings were:

(1) Revegetation of the old road was satisfactory 8 years after restoration.

(2) Species colonising the rehabilitated road were dominated by those present in land fill, which came from the Simpson Land System regardless on which land system they were situated.

(3) The extrinsic attribute with highest correlation to the composition of herbaceous species in the absence of disturbance was rainfall over the previous 6–48 months.
(4) Erosion was reduced and observed to become negligible following the construction of diversion banks.
(5) Brush cover did not have any effect on speed of revegetation nor on floristic composition over the 8 years of monitoring.
(6) Burning initially slowed revegetation but, after 8 years, there was no difference between burnt and unburnt sites.
(7) No vegetation type was stable and even on reference sites some change in dominance was evident.
(8) The method described for rehabilitating a road in the arid zone is satisfactory on the same land system from which the filler soil is sourced but restoration to adjacent undisturbed vegetation is not achieved with filler soil from a different source.

In summary, the aim of producing vegetation cover, that is ecologically sustainable and as close to the original state as possible, was partially achieved. Even after 8 years, however, the rehabilitated sites were still dissimilar and much more variable in plant species composition than the reference sites.

Future management could include additional monitoring to include not only plants but also ground-living invertebrates, particularly decomposer organisms, as their density and composition in undisturbed vegetation, compared with rehabilitated sites, could give a more complete indication of sustainability and resilience of the restoration efforts than that of plant data alone.

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