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# Accounting for the Drivers that Degrade and Restore Landscape Functions in Australia

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This Supplementary supports the main text as follows:

**Table S1.** List of 10 sites assessed using the VAST-2 criteria and indicators of structure, species composition and function (Table 2) showing the associated agro-climate regions, bioregions and plant communities.

| Site No. | Agro-Climate Region | Bioregion | Plant Community | Site Name | Site Location |
|---|---|---|---|---|---|
| 1 | Cold wet | Victorian Alps | Poa tussock grassland | Rocky Valley, Bogong High Plains | 36°54'9.26"S 147°17'22.19"E |
| 2 | Temperate cool-season wet | South Eastern Highlands | Eucalypt open forest | Blundells Flat, Brindabella Range | 35°19'10.46"S 148°49'20.07"E |
| 3 | Mediterranean | Kanmantoo | Callitris–eucalypt low mallee woodland | Wirilda, Harrogate | 35° 0'1.33"S 139° 1'25.69"E |
| 4 | Temperate - Sub-humid | NSW South Western Slopes | Tussock grassland Eucalypt open woodland | Winona, Gulgong | 32°10'36.70"S 149°33'39.34"E |
| 5 | Sub-tropical Sub-humid | Brigalow Belt South | Acacia open forest and woodland | Potters Flat, Wandoan | 26° 9'47.56"S 149°35'0.45"E |
| 6 | Sub-tropical moist | South Eastern Queensland | Lowland sub-tropical rainforest | Rocky Creek Dam, Big Scrub | 28°38'8.54"S 153°20'32.58"E |
| 7 | Tropical warm season wet | Ord Victoria Plain | Eucalypt open woodland | Conkerberry Paddock, Victoria River Research Station | 16°04'24.8500"S 130°56'49.60"E |
| 8 | Tropical warm season moist | Central Queensland Coast | Imperata - Themeda tussock grassland | North Molle Island, Molle Group, Cumberland Islands | 20°13'48.0500"S, 148°49'26.56"E |
| 9 | Tropical wet | Wet Tropics | Complex mesophyll vine forest | Wooroonooran Nature Refuge | 17°23'15.44"S 145°43'33.83"E |
| 10 | Dry | Coolgardie | Eucalypt woodland | Chadwin paddock, Credo Station | 30°20'43.38"S 120°43'30.08"E |

**Table S2.** Descriptions of agro-climatic regions.

| Site No. | Agro-Climatic Region Name [13] |
|---|---|
| 1 | Cold wet<br>The climate is predominantly wet and cool, to warm, with strongly winter dominant rainfall. The relatively high rainfall is strongly influenced by mountainous areas, above 1500 m, with peaks above 2000 m. In mountainous areas there is a general gradation in vegetation with elevation, with eucalypt forests giving way to eucalypt (snow gum) woodlands in subalpine areas and herbfields and tussock grasslands in the Alpine zone. Natural vegetation varies from tussock grassland to eucalypt woodlands and open forests and cool temperate rainforest. Much of the region is used extensively for nature conservation, forestry, hydroelectricity generation and tourism.<br>Modified from [15] - Wet temperate coast. |
| 2 | Temperate cool season wet<br>The climate is predominantly cool and wet summers becoming drier and hotter towards the inland. The relatively high rainfall is strongly influenced by tablelands. The native vegetation is predominantly eucalypt open forests and woodlands. At lower elevations large areas have been cleared for intensive agriculture including cropping and horticulture in combination with livestock grazing. At higher elevations woodland and forest been cleared for sheep and cattle grazing and for plantation forestry. Large areas of native forest have been retained which are used for forest production and nature conservation, and are also important for water harvesting.<br>Modified from [15] - Wet temperate highlands |
| 3 | Mediterranean<br>The climate is characterised by hot summers, cool winters and a winter dominant rainfall. The unmodified native vegetation is characterised by eucalypt casuarina and Acacia woodland and forest with chenopod, mixed and acacia shrubland. This region has been extensively cleared for cereal cultivation and temperate pastures and represents the heartland of Australia's agriculture.<br>Modified from [15] - Temperate seasonally dry slopes and plains |
| 4 | Temperate sub-humid<br>The climate is warm although the winters are mostly cool. Rainfall is generally uniformly distributed in the south tending to summer dominance in the north. The unmodified native vegetation is grassy eucalypt woodlands and shrubby forests. Much of the region has been extensively cleared and replaced with exotic pasture and cropping in combination with livestock grazing, both sheep and cattle. Coal mining and coal seam gas extraction are increasingly important land uses.<br>Modified from [15] - Sub- humid, subtropical highlands |
| 5 | Sub-tropical sub-humid<br>The region has hot summers and mild winters with the rainfall intermediate between wet subtropical coast and semiarid sub-tropical plains. Rainfall distribution tends to a summer dominance, particularly in the north. Cracking clay soils are extensive throughout the region. The unmodified vegetation is dominated by eucalypt open forest and woodlands and by acacia (brigalow) open forest. Much of the region has been cleared and converted to improved pasture and cropping. Grazing of cattle is also important in association with modified pastures and cropping.<br>Modified from [15] - Sub- humid subtropical slopes and plains |
| 6 | Sub tropical moist<br>The climate is warm and wet with a uniform summer dominant rainfall. Native vegetation is primarily tall eucalypt forest with areas of subtropical rainforest. Much of the region has been cleared for dairying, beef grazing, intensive cropping and horticulture. Native forestry and tourism are also important. Coal mining and coal seam gas extraction are increasingly important land uses. This region also supports the highest population densities in Australia.<br>Modified from [15] - Wet subtropical coast) |
| 7 | Tropical warm season wet<br>The climate is characterised by marked seasonal rainfall distribution with significant wet hot summer and dry warm winter seasons. The native vegetation includes eucalypt grassy woodlands and forest, as well as melaleuca and acacia woodlands. Small area of tropical rainforest occur in sheltered areas and in areas with access to ground-water. In some areas |

| | |
|---|---|
| | extensive native grasslands predominate on cracking clays. In the drier areas low open eucalypt woodland and acacia shrubland and hummock grassland are also common. Beef cattle production is extensively practised. Across the region there are small areas of irrigated crops and horticulture that are made possible by accessing local groundwater systems in the dry season. Tourism, nature conservation and indigenous land management are also important in the region.<br>Modified from [15] - Wet/dry Northwest tropics, Wet/dry north-eastern tropics and Semiarid tropical and subtropical plains |
| 8 | Tropical warm season moist<br>The climate is characterised by non-seasonal temperature regimes and a rainfall regime that is uniform or has a short dry summer. The native vegetation is characterised by medium tall eucalypt forest and sub-tropical rainforest. Much of the native vegetation has been cleared for intensive cropping often in association with cattle grazing. Tourism is an important land use.<br>Modified from [15] - Wet tropical coast and tableland |
| 9 | Tropical wet<br>The climate is characterised by non-seasonal temperature regimes and a predominant wet summer rainfall regime. The native vegetation is predominantly eucalypt open forest and tropical rainforest. Areas with gentler slopes and plains have been extensively cleared for intensive horticulture and cropping. Steeper and higher elevation areas have retained much of the forest vegetation which is important for nature conservation and tourism.<br>Modified from [15] - Wet tropical coast and tableland |
| 10 | Dry<br>The climate is warm to hot semiarid to arid encompassing the diversity of soil geology and vegetation. The native vegetation is predominantly low woodlands of Acacia, eucalypt and casuarina, chenopod shrubland, and hummock grassland. The region is extensively history of livestock grazing. In addition, large areas are managed for nature conservation, indigenous land management, mining and tourism.<br>Modified from [15] - Temperate semiarid plains and arid interior |

## Case Studies 1–10

### *Case Study 1: Rocky Valley*

*Agro-Climate Region: Cold Wet*
*Rocky Valley, Bogong High Plains, Victorian Alps bioregion. Plant community: Poa tussock grassland. Area: 25 ha*

A site excluding cattle grazing was established in the mid-1940s and thereafter was regularly monitored to assess the impacts of grazing and fire on the soils and vegetation [S1,S2]. Compared to other more heavily impacted sites in the Victorian high country, this site was minimally modified during this period. Information used in this assessment was collected at this exclosure [S3].

Case study 1 on the Bogong High Plains comprises a treeless alpine grassland, with isolated low shrubs. During winter the site is snow-covered and by late spring the snow melts providing a brief growing period over summer (Table S2). The indigenous reference state plant community is an open tussock grassland dominated by snow grass (*Poa hiemata*) located on flat to gently sloping areas south of the Rocky Valley Dam [29]. Figure 2 presents a summary of the transformation of the Rocky Valley grassland.

By the late 1840s indigenous people were displaced and gold prospectors had established small mining operations in the region however the Rocky Valley site was *Unmodified* (80–100% of the reference state). Pastoralists discovered the Plains in 1851 [S4].

In the period 1850s to the late 1890s increasing numbers of graziers moved their stock, mainly cattle, from the lowlands to the high country as soon as the snow melted in spring. High country pastures were grazed over spring and summer months (i.e., regime 2, Table 1). In response to the observed changes the impacts of cattle grazing the Victorian Government in 1866 intervened by establishing leases and licences because in some areas extensive overgrazing was recorded. These regulations controlled the number of grazing licenses however these permits did not limit the total grazing pressure or the grazing season [30]. In droughts additional stock, including between 18,000 and 20,000 sheep, were overlanded to the high country [S4].

In the period 1900s to the late 1930s large numbers of stock were using the Plains for grazing over spring and summer. During periods of drought high numbers of cattle and sheep were being grazed on the alpine pastures. In this period the backcountry recreation, e.g. skiing, bushwalking and wildflower appreciation were becoming increasingly popular. Use of the area including summer and winter activities was increasing. The development of a hydro-electric scheme in the lowlands necessitated the mitigation of erosion which was occurring in the alpine grazing areas. While soil erosion became a pronounced problem across the Plains, the tussock grasslands of the Rocky Plains remained in an *Unmodified* state (80–100%).

In the period between the 1940s and the late 50s the Victorian Government intervened to reduce the degree of erosion occurring in the high country. Grazing leases were withdrawn, sheep were banned, and the entry and departure dates for cattle were set [S4]. The Soil Conservation Board and cattle graziers agreed to limit cattle grazing on the Bogong High Plains. Cattle numbers were reduced and annual grazing periods were shortened. In 1946 a cattle exclusion plot was established to assess the impacts of grazing and fire and monitoring commenced in the response of plot and a nearby control [S1,S2]. Cattle numbers on the Plains were decreasing because of favourable seasons on the lowlands. The Rocky Plains tussock grasslands remained in an *Unmodified* state (80%–100%).

In the period 1960s-late 80s cattle numbers on the Plains continued to decrease. In 1981 the Bogong National Park was gazetted and cattle were removed from within Falls Creek resort area. The Victorian parliament in 1989 passed legislation which incorporated Bogong National Park into the Alpine Nation Park and excluded grazing from particular areas within it, but allowed it to continue in the remainder [30]. The Rocky Plains tussock grasslands remained in an *Unmodified* state (80%–100%).

In the period 1990s-2016 cattle have been excluded from the Rocky Plains (i.e., regime 5, Table 1) and the tussock grasslands remained in an *Unmodified* state (80%–100%).

Figure 2 shows the graphical assessment of the effects of the above land management practices on the structure, composition and function of the Poa tussock grasslands of Rocky Valley. Data and information used to score the indicators and criteria was obtained from several sources [29,30,S3,S4].

**Case Study 2: Blundells Flat**

*Agro-Climate Region: Temperate Cool-Season Wet,*
*Blundells Flat, Brindabella Range, South Eastern Highlands bioregion. Plant community: Eucalypt open forest. Area: 13 ha*

Following the agreement to establish Australia as a federation of six states and two territories in 1911, the location of a new national capital, Canberra within a new territory, formerly in New South Wales was selected, including the eastern fall of the Brindabella Range, of around 1300 m altitude. The climate is predominantly cool with relatively high average annual rainfall (790 mm) that is uniformly distributed throughout the year (Table S2). Rainfall is strongly influenced by north-south aligned tablelands intersecting predominantly easterly moving rain-bearing clouds. In 1915 this area including the catchment of the Cotter River was declared a water catchment area to supply Canberra. With the rapid expansion of Canberra urban area, there was a growing demand for native and softwood timbers for construction so pine plantations were established.

The indigenous reference state plant community is brown barrel *Eucalyptus fastigata* open forest. Figure 3) presents a summary of the transformation of the Blundells Flat Eucalypt open forest.

The site remained *Unmodified* prior to 1957 because of the steep terrain and remoteness from settled areas. During the period the area was witness to the displacement of indigenous people; traverses by European explorers; mineral fossickers and declaration of the area as a water catchment area for Canberra (i.e., regime 1, Table 1). In the latter part of this period some selective logging, mainly of brown barrel, was recorded (i.e., regime 2, Table 1) but had little impact of the site's structure, composition and function (Figure 3).

In the period between 1958 and 2003 the site was converted from native open forest into a *Pinus radiata* pine plantation (i.e., regime 4, Table 1) and managed for the production of pine chips. Initially, the eucalypt trees were clear-felled and millable logs were salvaged (i.e., regime 2, Table 1). The felled timber and other vegetation was pushed into windrows with a bulldozer and left to dry out for one year, after which it was burnt in summer. Large eucalypt stumps were not removed. Because of the steepness of the terrain first and second rotation pine seedlings *Pinus radiata* were manually hand-planted with small applications of superphosphate applied around every seedling. During the establishment of the pine seedlings competing regrowth native vegetation was manually controlled with axes, brush hooks, and hoes. Thinnings and prunings of the pines were left on the ground to decay. Mature first rotation pines were cut manually and the logs were snigged off the site using a crawler tractor. In planting and establishing the second rotation ripping was again not used because the site was too steep, although the herbicide Roundup was sprayed to kill regrowth native vegetation (i.e., regime 4, Table 1).

Over this period there was a very rapid decrease in the component scores for vegetation structure and species composition and a more gradual decrease in the component scores for function (Figure 3). The vegetation status of the site transitioned from *Unmodified* (i.e., 80–100% of the reference) through *Modified* (i.e., 60%–80% of the reference) to *Transformed* (i.e., 40%–60% of the reference).

In 2003 following a severe wildfire burnt coupe 427a, and surrounding softwood and hardwood forests; an area of about 5000 ha in Lower Cotter Catchment. In the ensuing months there was major soil erosion. Restoration involved using mechanical harvesters to cut, fell and windrow the dead pines. In addition, sterile rye corn grass seed was sown across the broader region using light aircraft to stabilise erodible soils. A decision was made by the Australian Capital Territory Government to re-establish the native open forest over most of the former pine plantation, using assisted restoration (i.e., regime 5, Table 1). On-ground manual contractors were engaged to remove pine wildlings by hand. The aim of the restoration activity was to rehabilitate the Lower Cotter Catchment toward the reference state [31]. Data and information used to score the indicators and criteria are published online [31].

Between 2003 and 2010, the vegetation status of the site remained in a *Transformed* state (i.e., 40%–60% of the reference). Since 2010, the area has been left to naturally rehabilitate and has been minimally managed in keeping with its gazetted land use, i.e., a water catchment area for the city of Canberra.

**Case Study 3: Wirilda**

*Agro-Climate Region: Mediterranean*

*Wirilda, Harrogate, Kanmantoo bioregion. Plant community: Callitris–Eucalyptus mallee low woodland.*

*Area: 18 ha*

This site is located east of the Adelaide comprising a grassy and shrubby low open woodland on the eastern slopes of the Mount Lofty Ranges. Rainfall is about 450 mm falling mainly in winter and spring (Table S2).

The indigenous reference state plant community is slender cypress pine (*Callitris gracilis*), Peppermint box (*Eucalyptus odorata*) and Mallee Box (*E. porosa*) are co-dominants over mallee *Eucalyptus anceps, Allocasuarina verticillata, Acacia retinodes, Acacia argyrophylla* over *Dianella revoluta* var., *Austrodanthonia* spp., *Austrostipa* spp., *Lomandra multiflora* ssp. *dura Lepidosperma viscidum, Maireana enchylaenoides*. Figure 4 presents a summary of the transformation of Wirilda's Callitris–Eucalyptus mallee low woodland.

In the period between 1800 and 1883 the vegetation status of the Wirilda site remained in an *Unmodified* state (i.e., 80–100% of the reference). This period included displacement of indigenous people, traverses by explorers and mineral fossicking. Early pastoralism (i.e., regime 1, Table 1) with shepherds and sheep grazing had minimal effects on indicators of structure, composition and function as shown in Figure 4.

During the period between 1883 and 1974 the site was subject to intensive management practices including very heavy cutting of tree cover to supply timber for Callington and Kanmantoo copper mines (i.e., regime 1, Table 1). The native ground cover was converted to oats by regular ploughing of the soil, sowing with oats and regular applications of superphosphate. Over this period the pasture was converted from native to improved pasture (i.e., regime 4, Table 1). When the area was not cropped, the site was managed using set or continuous stocking with sheep and cattle.

Such management resulted in rapid decreases in the component scores for function, structure and composition (Figure 4). The vegetation status of the site was transformed from *Unmodified* (i.e., 80%–100%), through *Modified* (i.e., 60%–80%) and *Transformed* (i.e., 40–60%) to *Replaced/adventive* (20–40%).

In the period between 1974 and 2010 the site was gradually restored towards its original reference state (i.e., regime 5, Table 1). Applications of superphosphate ceased as did cropping and set or continuous stocking with sheep and cattle. Around 25,000 local indigenous trees and shrubs were propagated and hand sown as seedlings. The site was recognized as a reconstructed *Callitris–Eucalyptus mallee low woodland* and granted a covenant on the title deed in perpetuity. The site is maintained by regular and ongoing weed control (i.e., regime 3, Table 1). During this period the vegetation status of the site transitioned from *Replaced/adventive*, through *Transformed* to *Modified* (Figure 4).

The relatively fertile soils of the site have played an important role in the site being managed for almost 70 years under a system of mixed cropping and continuous/set stocking with sheep and cattle. This assessment documents the declining resilience of the site under the effects of that agricultural history and rehabilitation of the site being toward the reference state commencing in the early 1970s, through intensive propagation of locally collected indigenous trees and shrubs species [S5]. As a result of the vision and practice of an individual, there are now numerous landholders in the local area adopting similar rehabilitation practices. The site is also an exemplar area for regional bodies, state government and national conservation agencies.

Data and information used to score the indicators and criteria are published online [S5].

**Case Study 4: Winona**

*Agro-Climate Region: Temperate, Sub-humid*

*Winona, Gulgong, NSW South Western Slopes bioregion. Plant community: Grassy eucalypt open woodland. Area: 13 ha*

Winona site located near Gulgong, NSW was an open woodland or woodland up to 30 m tall. The climate is warm although the winters are mostly cool. On average, 650mm of rain falls with a slight summer bias. Soils on the site are Euchrozems (deep red clay loams) that developed on basalt (Table S2). The first wheat was grown in the area in the late 1890s. Removal of the overstorey eucalypts commenced in the 1890s and was completed by 1930. In the period 1931-50 native pastures were managed in combination with rain-fed wheat cropping and continuous stocking with sheep. This farming system is characterised by a 3 yearly repeated cycle of sheep grazing followed by repeated ploughing and intensive applications of superphosphate to grow wheat. Between 1950 to 1970 the native pastures were converted to improved pasture dominated by Subterranean clover (*Trifolium subterranean*). The conventional farming system continued from 1931 to 1990. The history of this site, is similar to many others like it, on the western slopes of New South Wales and represents some of the most productive sheep and wheat country in Australia. In 1991 a major transformation occurred at the site involving the cessation of the conventional farming system and the adoption of direct drilling of wheat into winter dominant native pastures and rotational grazing with sheep. This system farming is described as rotational grazing and pasture cropping. This assessment documents the resilience of native pasture grasses under these management regimes.

The indigenous reference state plant community is *Angophora floribunda*, *Eucalyptus blakelyi*, *Eucalyptus melliodora* open woodland - woodland/ *Acacia implexa* open shrubland over an *Austrostipa verticillata* open tussock grassland. Figure 5 presents a summary of the transformation of Winona's grassy eucalypt open woodland.

Land squatters and settlers arrived in the area in 1820s–30s and began modifying the herb-rich grassy understorey with small flocks of sheep attended by shepherds.

With the arrival of wire in the 1870s, boundary paddock fences soon replaced the need for shepherds and sheep management moved from open grazing to set stocking or continuous grazing. By the 1880s broadscale tree ring barking was used to promote native pasture within paddocks. By the 1890s regrowth eucalypts saplings were invading the pastures. In 1895 a small area of wheat was grown between the widely spaced trees which proved highly successful. In the following years wheat continued to be grown on a small scale, highlighting the value of naturally rich well-drained basalt soil to produce wheat.

In the period 1898–1930s regular ring barking of eucalypt seedlings was needed to maintain open pastures.

In the 1914–20s European rabbits arrived in the district and proved to be a major problem with wheat growing and competing for pasture with the sheep. In the mid-1920s rabbit proof fencing become available and this was erected around the boundary of the property and around key cropping paddocks.

In the period 1928–30 initially small areas were managed by annual sowing and harvesting of wheat and grazing with 700 sheep. With annual cropping declining yields were observed. In 1931 tractors replaced horses for towing cropping equipment.

In the period 1931–92 paddocks were managed on a three-year cycle i.e., three years of mixed cropping and three years grazing pasture. In the years 1931 to 1950 pastures were native grasses, however between 1950 to 1970 pastures were converted to 'so-called' improved pasture dominated by Subterranean clover (*Trifolium subterranean*). Superphosphate was applied in both the cropping pasture cycles to maintain productivity. Throughout this period three yearly cycles of cropping and grazing, 700 sheep were continually grazed using set stocking. In the cropping years each paddock was ploughed five times to reduce the germination of native pasture species so that is successful germination of wheat could be established. This type of agricultural production is described as conventional farming system.

In 1978 summer rainfall above average followed by the low average rainfall in 1979. A severe wildfire in 1979 caused considerable losses of crops, sheep, fences, farming equipment and buildings [S6].

In the period 1980 to 1990 major changes were made to the conventional farming system. Rather than repeated ploughing at the start of each cropping cycle to reduce the virulence of pasture species, a weed-killer was applied prior to sowing wheat to kill native grasses, clover and weedy species associated with cropping. Also commencing in 1980, superphosphate was only added in the cropping cycle and not in the grazing cycle. A considerable improvement was observed in the tilth of the soil due to less frequent mechanical working. Improvements are also observed in the grass sward of native species prior to sowing wheat [S6].

In 1991 the conventional farming system ceased along with all applications of superphosphate.

In the period 1993-2016 a new system called rotational grazing and pasture cropping with native pasture was initiated [S7].

Continued improvements in the soil and vegetation condition of the native vegetation have been observed and monitored as the early 2000s [S7, S8].

Data and information used to score the indicators and criteria was obtained from several key sources [S6-S8].

**Case Study 5: Potters Flat**

*Agro-Climate Region: Sub-Tropical Sub-Humid*

*Potters Flat, Wandoan, Brigalow Belt South bioregion. Plant community: Acacia forest and woodland. Area: 2.5 ha*

Brigalow (*Acacia harpophylla*) once formed extensive forest and woodland on communities with a variable rainfall ranging from 500 to 750 mm annual rainfall (Table S2); and extended from central Queensland into central northern New South Wales [S9]. The area's naturally fertile cracking clay-loam soils, variable and relatively high year-round rainfall and mild temperatures made it an ideal candidate for agricultural development. Many decades of failed attempts to clear and re-clear the Brigalow were based on a seemingly insurmountable problem, that of sucker regrowth resulting from ring barking, felling, chaining and pulling the regrowth. However, in the 1950s and 60s lessons gained from using chemical control combined with repeated mechanical clearing showed that Brigalow lands could be cleared and converted to agriculture. In the early 1960s state and

Commonwealth agencies provided funding for long-term loans to approved settlers for land development on the basis that they converted the Brigalow to agriculture. By the early 1990s, large tracts of *Unmodified* Brigalow had been converted pasture and/or cultivation i.e., *Replaced and managed*. In the late 1950s several small patches of regrowth were retained and managed as shelter belts for cattle [S10]. This assessment documents the resilience of these patches of regrowth, which in themselves were subject of repeated attempts to remove the Brigalow in the wider Potters Creek paddock.

The indigenous reference state plant community is Acacia forest and woodland. Figure 6 presents a summary of the transformation of this plant community at the Potters Flat site.

Figure 6 shows that prior to the 1830s the brigalow woodland (*Acacia harpophylla*) at Taroom, Queensland was *Unmodified*, that is the site had no interventions that effected the structure, composition and function (i.e., regime 1, Table 1). This is the reference state. After this period the herb-rich-grassy understorey was lightly-grazed with sheep using shepherds; the effect of this intervention was minimal (regime 2, Table 1). The first round of land clearing occurred in the mid-1930s using ringbarking with axes resulting in higher stock numbers than during the time of shepherding. In 1961 the overstorey was pulled mechanically and the understorey soil was ploughed and sown to buffel grass (*Cenchrus ciliaris*) (i.e., regime 4, Table 1). The surrounding brigalow regrowth was re-cleared and annually sown to wheat, while this patch was allowed to regenerate between 1961 and 1970 as an unfenced shelter belt for cattle (Figure 6). The site from 1961–70 shows a rapid recovery of the structure (1%–5%) followed by a more gradual increase from 1971–2010 (8–15% of a potential 27% of the benchmark vegetation structure) (i.e., regime 4, Table 1). Over the same period the site shows a gradual increase in the species composition (5%–10% of a potential 18% of the benchmark species position.

The relatively intensive use of the shelterbelt by cattle since 1971, through browsing, trampling and fertilising by defecation and the introduction of weeds [S10], have resulted in a declining function of the site compared to an unmodified reference state, namely; soil nutrients, soil physical and hydrological state and the reproductive potential of the plant community (regime 4, Table 1). While the structure of the overstorey is currently improving (regime 3, Table 1), the understorey structure is declining (regime 4, Table 1). Similarly, the composition of the overstorey is being maintained however, the composition of the understorey is declining.

Overall the site has been transformed over time as follows: up to 1830 it was *Unmodified*, between 1880-1950 the site was in a *Modified* state, and since 1951 the site has been managed as a *Transformed* state.

Data and information used to score the indicators and criteria are published online [S10].

**Case Study 6: Rocky Creek**

*Agro-Climate Region: Sub-Tropical Moist*

*Rocky Creek Dam, Big Scrub, South Eastern Queensland bioregion. Plant community: Lowland sub-tropical rainforest. Area: 25 ha*

The "Big Scrub" was once a vast area of lowland subtropical rainforest covering approximately 75,000 hectares associated with the Mount Warning Volcanics. The area's naturally fertile basaltic soils, a reliable year-round rainfall in excess of 1300 mm and mild temperatures made it an ideal candidate for development of small agricultural farms (Table S2). Commencing in the mid-1800s the New South Wales government gave allotments to potential farmers on the basis that they converted the rainforest to agriculture. The landscape was largely transformed into intensively managed smallholdings by the 1910. Today less than 1% of the area of the original rainforest remain. Extant areas of rainforest are important focal points for local and regional communities as well as these remnant areas have been recognised at state, and national and international levels, forming part of the Gondwana Rainforests of Australia; and are a World Heritage Site. This site documents the transformation of a former dairy farm that has been rehabilitated toward the reference state of subtropical lowland rainforest [S11]. These findings are supported by studies of the resilience of subtropical and tropical rainforests [S12].

The indigenous reference state plant community is Lowland Subtropical Rainforest. Figure 7 presents a summary of the transformation of the Rocky Creek Dam rainforest.

The chronology for Rocky Creek Dam extends from the first record from Europeans in the general area in 1840 to 2010 [S12]. Between 1840 and 1910 the site was *Unmodified* Complex, i.e., reference state (100%) Notophyll Vine Forest [S13], also termed Lowland Rainforest [S14]. The site was selectively logged in 1910, when the larger cedar trees were removed [S11]. The effects of this management practice were negligible when scored across all 22 indicators, and summed across the associated ten criteria and three components of vegetation condition as shown by a Vegetation Status score of 100%.

Between 1911-1949 the rainforest was cleared and converted to farmland including improved pasture for dairy cattle (i.e., regime 4, Table 1). This regime had major effects on all condition components, and in particular structure and composition, although proximity to a seed source meant there was some residual regenerative capacity remaining (i.e., down from a score of 55% in 1911 to 40% in 1949 as a result of establishing exotic pastures for grazing dairying cows). In 1949 the site was purchased as a water supply catchment and other uses ceased.

In the period between 1950 and 1982, following the abandonment of dairying (i.e., regime 1, Table 1), lantana (*Lantana camara*) invaded and became the dominant vegetation cover until 1988. During this time of nil management, lantana maintained the site in a state where the vegetation structure (i.e., 0% of the benchmark condition), species composition (10% of the benchmark) and function was (43% of a potential 55% of the benchmark).

Between 1983 and 2010 initially an experimental area was transformed between 1983 and 1989 by restoring the Rainforest structure and composition by controlling the lantana (i.e., regime 5, Table 1). Over this period the structure was restored to 92% of the benchmark and composition was restored to 72% of the benchmark. Because the function of the site was the least affected of the three components of condition prior to 1988, it provided a higher starting base and was transformed to 98% of the benchmark. Commencing in 1983, restoration lessons learnt from the experimental area, were scaled up to include a larger area which was largely completed in 1999, covering an area of 25 ha.

The process used was to systematically convert small compartments (15 in total) covered almost entirely with lantana, back towards the original Lowland Subtropical Rainforest's composition, structure and ecological function [S15]. The main technique used was to mechanically slash the lantana to create ground cover mulch and then, as germination of the lantana was observed, use weed killer to halt its re-establishment. These authors present several reasons for the success of the regeneration of the site including: the site's proximity to a large native remnant rainforest; a sound understanding of the biology and ecology of lantana; a sound working knowledge of where natural reproductive potential exists; and how it was progressively implemented in new areas once an established area became self-sustaining.

By 2001 the site had added almost 25 ha of *Modified* Lowland Subtropical Rainforest to the eastern boundary of a much larger area of *Unmodified* Lowland Subtropical Rainforest formally protected in the Big Scrub Flora Reserve.

Data and information used to score the indicators and criteria are published online [S11].

**Case Study 7: Conkerberry Paddock**

*Agro-Climate Region: Tropical Warm Season Wet*

*Conkerberry Paddock, Victoria River Research Station (Kidman Springs), Ord Victoria Plain bioregion. Plant community: Eucalypt open woodland. Area: 41.6 ha*

The climate of the tropical savannas is characterised by marked seasonal rainfall distribution with significant hot wet summer and warm dry winter (Table S2). As noted above the region is regarded as an ecotone between Tropical warm season wet and the Dry continental region [14], which since the 1970s has generally received more rain and the wet season have extended from summer into autumn [19]. This has coincided with a general increase in the cover and density of woody tree cover across the tropical savannas [19,S16].

The Research Station was once an important stock reserve on the main east west route between the Kimberley to Queensland. At various times the stock reserve held large stock concentrations of cattle and as a result the majority of the area is in some state of deterioration, especially near permanent waterholes [S17]. This vegetation association has been seriously influenced by excessive stocking and in many areas almost all the trees are dead and there is evidence of soil loss as shown by exposed tree butts and roots and large bare scalded areas [S17]. This assessment documents the obvious changes in structure, composition and function over time representing an example of a site that is a 'tragedy of the unmanaged commons' [S18].

The indigenous reference state plant community is Eucalypt open woodland. Figure 8 presents a summary of the transformation of this plant community in the Conkerberry Paddock.

Kidman Springs research station was essentially unmodified until the time that cattle arrived in the area which was in late 1870s. Up to this time Aboriginal people played a key role in the management of the grassy woodlands, using fire stick farming throughout the dry season; burning systematically and purposefully for a diverse range of ecological and pervasive social values [S19].

Between the 1880s and up till the early 1900s cattle numbers were small and would have had a minimal effect on the area.

The in the period between the early 1900s up to the mid-1920s cattle numbers on the Victoria River downs station rapidly increased from the small population of the early 1900s. It is likely that the stock reserve was established in the 1920s when cattle numbers had reached an equilibrium with the available feed and water in the dry season.

In the period between the mid-1920s to the early 1960s cattle numbers fluctuated in response to the seasonal conditions. With few if any fences, cattle ranged widely across the landscape only returning to water points, primarily the major creeks and rivers, in the dry season. During major droughts i.e., when there was a failed wet season many thousands of cattle died and considerable damage was done to the landscape particularly near permanent water. Essentially cattle were free to breed up, and to range widely, and in many respects their populations were self-managing.

By the 1960s it was recognised by government regulators and the station managers that a major limiting factor in the production of cattle from these savanna landscapes was a lack of strategically placed water points available to cattle in the dry season. Numerous bores were established and cattle continued as they had in the decades previously, ranging freely without constraint of fences.

Up to the early 1960s, cattle were harvested for live cattle export at the end of the dry season, by droving herds of cattle over very large distances by skilled stockman travelling via stock routes and stock reserves. By the mid-1960s cattle road trains had replaced stockman droving cattle. The role and importance of stock routes and stock reserves then declined. In 1968 the Northern Territory government acquired the Kidman Springs stock reserve.

Up to the end of the 1960s, the Victoria District had a relatively short wet summer season and a much longer dry season (autumn, winter and spring). The dominant understory was described as arid shortgrass (Ennenpogon spp.) [S17]. From the 1970s to present day the wet season has extended from summer into autumn and more rain has been received. This is coincided with an observed increase in the cover and density of trees and shrubs in the landscape, which have competed with the available fodder for livestock, particularly in the dry season. Research and monitoring, combined with experiments at the Kidman Springs have tracked the recovery of degraded sites and of investigated various fire treatments for the control of woody plant incursions [S20].

In 1970, the introduction of the Brucellosis and Tuberculosis Eradication Campaign resulted in considerable change in the Victoria Rivers District, and across northern Australia. This program initiated several major changes in land management: (a) fences were established and maintained, (b) this enabled improved herd and pasture management (c) enabled control of very large numbers of feral donkeys and horses, (d) enabled improved water point management and (e) operational research and monitoring and reporting changed the way the site was understood and managed. The observed improvement in the condition of the vegetation index for the Conkerberry Paddock can be attributed to these outcomes, i.e., improvements in the herd management, the management of native pastures and soil condition.

In the early 2000's the Northern Territory government initiated a major fire research and monitoring program to encourage early dry season burning to improve production and biodiversity outcomes. It is unclear whether this practice has been implemented across the Research Station.

Data and information used to score the indicators and criteria was obtained from several key sources [19,S16-S20].

**Case Study 8: North Molle Island**

*Agro-Climate Region: Tropical Warm Season Moist*

*North Molle Island, Molle Group, Cumberland Islands,* Great Barrier Reef, *Central Queensland Coast bioregion. Plant community: Imperata-Themeda tussock grassland. Area: 130 ha*

North Molle Island was first charted by Captain James Cook on the 4th June 1770, while sailing on the landward side of the Great Barrier Reef, when he named this and other islands part of the Whitsunday Group [S21]. The Whitsundays have a tropical climate of hot summers and warm winters. Rainfall is the heaviest in the months of January to March, with yearly rainfall being a function of the occurrence of cyclones which can occur between February and March (Table S2). While this route provided a relatively safe passage during storms, shipwrecks were however common, given the absence of bathymetric charts. As a result, goats were regularly placed on many of the islands between 1852 and 1888 to provide a food source for shipwrecked sailors [S21]. Between 1770 and 1855 there are numerous records of the early European explorers observing that Aborigines used of the islands [S22] and frequently noted smoke generated by aboriginals burning grasslands. Burning was practiced on most islands of reasonable size adjacent to the mainland [S23]. The reasons why aboriginal people burnt these islands remains a mystery.

This assessment documents the transformation of grassland to a shrubland resulting from the loss of an indigenous fire regime and the removal of grazing pressure. The reference state, and that observed by the early European explorers in 1770–1800, is that of a grassland derived by deliberate management by Indigenous peoples. Coastal indigenous people regularly used fire in combination with seasonal patterns of rainfall, prevailing winds and effects of cyclones to modify the structure and composition of the vegetation [28].

The indigenous reference state plant community is *Themeda triandra* and/or *Imperata cylindrica* and/or *Chionachne cyathopoda* tussock grassland to closed tussock grassland, or *Xanthorrhoea latifolia* subsp. *latifolia* dwarf open shrubland to open heath, i.e., Regional ecosystem (RE) 8.12.13a [24], rather than an open shrubland to closed-scrub dominated by *Timonius timon* with *Pittosporum ferrugineum* as it is today under current park management i.e., Regional ecosystem (RE) 8.12.13b [24]. Figure 9) presents a summary of the transformation of the Imperata - Themeda tussock grassland.

In 1881 HMS Albert's charts of Port Molle describe North and South Molle Islands as grassland [S23]. In the early and mid-1800s the New South Wales government, which administered the area that would become Queensland, was keen to promote pastoralism. The first Occupation Licence over North Molle Island was granted in the early 1880s and sheep grazing commenced in 1883 [S21].

In the period 1883 to 1938 sheep grazing was the only land use on the island. The island was declared as the Molle Island National Park in 1938. All sheep were removed at this time. Goats persisted on the island from 1852, to 1993, when the last goats were removed by shooting. It is worth noting that the density of goats on the island in the mid-1980s had not caused an obvious loss of grass cover or resulted in large areas of bare ground [26].

An aerial photograph taken in 1945 was used to map the northern and central areas of the island as 90% open grassland, i.e., Regional ecosystem (RE) 8.12.13a and 10% scattered trees, i.e., RE 8.12.13b. Another aerial photograph taken in 1975 was used to map the same area as 51% open grassland, i.e., RE 8.12.13a and 49% scattered trees, i.e., RE 8.12.13b. By the 1980s *Timonius timon* (8.12.13b) was observed to have increased its cover and density to such an extent that it was displacing the *Chionachne cyathopoda* grassland community (RE 8.12.13a) [26].

Current management of the Island is based on a view that in the absence of grazing and wildfire, the Island would naturally return to its original pre-European state [27]. This illustrates the point of what is a reference state; that determined by government policy which reflects current social/human values and available resources or one that is based on evidence-based ecological research [28].

In the period 1986 to 1999 an on-ground fire research and experimental program was undertaken to determine the best fire regime to remove the shrub overstorey. That program was ceased in 1999. Since that time aerial incendiaries have been used, which has had the effect of promoting the development of the shrub layer over much of the island, except for the main north-south ridgeline, where more frequent burning has produced a grassy cover.

Since 2000 the island has continued almost unabated to become more woody. This includes the invasion of the grasslands by *Timonius timon*, initially as a shrub and over time turning into a low woodland. This also includes elements of littoral rainforest and vine thickets invading into these newly formed woodlands. Evidence observed in the field shows grass is outcompeted by shrub and tree growth forms that take advantage of the lack of frequent burning [25].

Data and information used to score the indicators and criteria was obtained from several key sources [24-28,S21-S23].

**Case Study 9: Wooroonooran**

*Agro-Climate Region: Tropical Wet*
*Wooroonooran Nature Refuge, Wet Tropics bioregion. Plant community: Complex mesophyll vine forest.*
*Area: 30.8 ha*

The Wet Tropics have a tropical climate of wet hot summers and warm winters. Rainfall is the heaviest in the months of January to March, with yearly rainfall being influenced by the occurrence of cyclones which can occur between February and March (Table S2).

This site, in far north Queensland, up until 1923 this area was an *Unmodified* of a Complex mesophyll vine forest [S13]. A policy decision of the Queensland Government to develop the district for dairying resulted in the conversion of the closed forest to exotic pasture grasses. Initially all high value timber species was selectively logged between 1924 and 1930.

The indigenous reference state plant community is Complex mesophyll vine forest [S13]. Figure 10 presents a summary of the transformation of the tropical rainforest found at Wooroonooran.

By 1938 the heavily logged forest including the litter and trash was burnt. What followed was the start of intensive soil and pasture management where aggressive pasture species, including molasses grass (*Melinis minutiflora*), was sown by hand into the ash bed. An early photograph of that period shows pasture grasses establishing around charred stumps and logs [26].

After one year of pasture establishment in 1939, grazing commenced in 1940. With the annual rainfall in excess of 4 m (Table S2 in the Supplementary Material), the soil soon became acidic due to the leaching of nutrients from the top soil. In the period between 1941–1947 tropical carpet grass (*Axonopus compressus)*, an invasive grass of low fertility soils quickly established. Over this period the soil condition was frequently ameliorated by applying large amounts of lime as a top dressing, to improve the productivity of the pastures. An aerial photograph, taken in 1943, shows a landscape completely cleared of trees and covered with grass. Relictual rainforest plants persisted only in the creeks and gullies.

In the period 1948–1957 dairying became increasingly marginal due to the high costs of production. As a result of this driver, in 1958 all livestock were removed. In the period 1959–1983 the land was minimally used or abandoned, leaving pastures that were increasingly dominated by weeds and infertile soils. An aerial photo, taken in 1960, shows lantana had invaded the pasture and regrowth rainforest occupying the deeper gullies and creek lines. The dominant tree in in the drainage lines was *Acacia celsa* along with tree ferns [26]. During this period, lantana played an important role in protecting the soil from erosion, by rebuilding soil nutrients and organic matter and assisting with infiltration of the very high rainfall and by acting as a cover crop protecting seed disbursed by birds and bats from the nearby remnant patch of rainforest [26].

In the early 1980s the land manager developed a plan to restore the agricultural productivity of most of the site and allow natural regeneration along the creek. In the period 1983–1991 the land manager controlled small areas of lantana by spraying and poisoning, with glyphosate, a weed killer, and by physically removing lantana from areas that were being regenerated. Over this period woody weeds progressively gave way to a greater number of volunteer rainforest species that germinated and established. It is assumed that seeds from the nearby area of remnant rainforest continued to be disbursed by birds and bats. By 1991 the gullies and creek lines and lower slopes were restored, creating a secondary succession complex i.e., *Modified* complex mesophyll vine forest.

In 1992 the remaining large areas dominated by lantana were bull-dozed by the land manager to remove the mature stands of lantana. The site was sold in 1993. In that same year, the intent of new owner was to progressively and systematically rehabilitate the whole site over the next 10 years to secondary rainforest [26]. This involved regular spraying with glyphosate of lantana, raspberry and carpet grass. Larger stems of lantana were cut with axes or ringbarked and stumps poisoned with glyphosate. These dead and decaying plants acted as a mulch assisting with germination, establishment and development of volunteer and planted seedlings. Over the period 1994 to 2002 many thousands of locally indigenous local rainforest seeds were collected and propagated to supplement the increasing numbers of volunteer rainforest species that germinated and established, creating a secondary succession complex over most of the site.

By 2002 the site had added almost 40 ha of *Modified* complex mesophyll vine forest to the western boundary of a much larger area of *Unmodified* complex mesophyll vine forest formally protected in Bartle Frere National Park.

In 2003 the Wet Tropics Management Authority formally gazetted this site as Wooroonooran Nature Refuge.

The resilience of this site is attributed to the incursion of exotic lantana acting as a cover crop, which for many years had protected the soil and rainforests seed that had been disbursed by birds and bats from the nearby Bartle Frere National Park [26]. In addition, to this natural 'seed rain', many thousands of indigenous local rainforest seeds were collected from nearby rainforest remnants and propagated to supplement this rapid transformation from exotic pasture grasses to secondary rainforest [26]. These observations of the dynamics of tropical rainforests have been described elsewhere [S12].

Data and information used to score the indicators and criteria are published online [S24].

**Case Study 10: Chadwin Paddock**

*Agro-Climate Region: Dry*

*Chadwin paddock, Credo Station, Coolgardie bioregion. Plant community: Eucalypt woodland. Area: 88 ha*

This site has an average annual rainfall 200–250 mm, with most useful rain being received in the winter months. Droughts of more than one year's duration are common (Table S2).

The indigenous reference state plant community is a salmon gum (*Eucalyptus salmonophloia*) open woodland, with sub- dominants comprising *E. transcontinentalis, E. gracilis, E. celastroides*. The understorey comprises numerous chenopod species on the ground layer consists of mainly annuals or short lived perennials. Figure 11 presents a summary of the transformation of the Eucalypt woodland found in the Chadwin paddock.

Fossicking for gold and small-scale gold mining commenced in the Great Western Woodlands [S25] in the 1860s. Located some 90 km south-east of the site, major gold bearing ore bodies were discovered near Kalgoorlie in the late 1800s. To extract that gold from its mineral bearing ore, wood-fired furnaces burnt large volumes of timber from across the region. This site is one of many areas in the region, surrounding Kalgoorlie, where larger woodland trees were felled and transported to run the wood-fired smelters in Kalgoorlie. This operation, known as timber-lining, supplied wood from this site to Kalgoorlie, some 90 km away.

In the period 1864–1895 indigenous people were displaced, explorers traversed the landscape in search of pastoral lands and gold prospectors established numerous small scale gold mines in the district (i.e., regime 1, Table 1). The early establishment of pastoralism with shepherds and harvesting of small amounts of timber for local mining operations are expected to have had minimal impact on the overstorey vegetation structure, species composition and function in this period (i.e., regime 2, Table 1). During this period the vegetation status of the site remained *Unmodified* (80%–100% of the reference state).

In the period 1895 and 1905 the site was heavily cut-over with axes by felling all solid-wood standing trees. Solid logs were supplied to the gold smelters in Kalgoorlie. All larger diameter trees were cut and removed from the site using tram lines. Timber lining, as it was known [S26], had an obvious impact on the overstorey indicators of vegetation structure but a minimal impact on indicators of function and species composition (i.e., regime 2, Table 1). During this period, the site transitioned from *Unmodified* (80%–100%) to *Modified* (i.e., 60%–80% of the reference) (Figure 11).

In the period 1905–1931 boundary and paddock fences were established and continuous stocking with cattle commenced in 1906–1907. Immediately following the harvesting of the timber there was minimal pressures from grazing, because the pastoral industry was only fledgling and the numbers of sheep and cattle were yet to breed up into sizable flocks and herds. Paddock fences were established in 1906–1907 and the continuous stocking with cattle commenced. Grazing with cattle continued until 1923. Rabbits arrived in the district from the south east around this time. Sheep replaced cattle in 1925. Water storages, including relatively small tanks and dams, were built with horse drawn implements. These provided only intermittent water supplies in average and good rainfall years. There was a steady decline in gold mining activity in the district. In the latter part of this period very high sheep numbers were present in the region. Regarding the vegetation status of the site, there was a transition from an *Unmodified* class (i.e., 80%–100%) to a *Modified* (i.e., 60%–80%) over this period.

In the period between 1931 and 2007 the site was part of a station-wide establishment and development of larger more permanent surface water holder storages (tanks and dams) and the installation of polyethylene piping and troughs. These practices had the effect of spreading the grazing pressure more evenly over larger areas and also in enabled larger numbers of stock to be carried longer into drier periods (i.e., regime 2, Table 1). Between 1932 and 1937 a major drought resulted in the deaths of large numbers of sheep in the region. In the period from 1960 to 1990, at the onset of prolonged droughts, young and breeding stock were transported to a family property located near Esperance. During these droughts older stock and weathers were sold rather than carrying large number of sheep into and through droughts. From 1990 to 2007 cattle replaced sheep. Regarding the vegetation status of the site, there was a transition from a *Modified* (60%–80%) to an *Unmodified* (80%–100%).

In the period between 2007 and 2012 Credo Station was purchased by the Western Australian government as a proposed conservation reserve (i.e., regime 5, Table 1) in part because the station had been conservatively managed since the 1930s. The station was destocked of cattle and several earthen dams and tanks were decommissioned along with all polyethylene piping and troughs. Regarding the vegetation status of the site, it remained in the *Unmodified* class (i.e., 80%–100%).

This assessment documents the resilience of a semi-arid open woodland through clear-felling of the mature trees, continuous/set stocking initially with cattle, and later with sheep, and again later with cattle. Conservative stocking rates and well-placed watering points, spread the total grazing pressure, resulting in the gradual recovery of the woodland [S27]. The primary driver of change, since the major drought of the mid 1930s, appears to be the intent of the land manager to develop a sustainable grazing enterprise.

Data and information used to score the indicators and criteria are published [S27].

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