Assisted natural regeneration accelerates recovery of highly disturbed rainforest

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Summary

Large areas of rainforests in Australia and other tropical regions have been extensively cleared since the mid 19th century. As abandoned agro-pastoral land becomes increasingly prominent, there is an ongoing need to identify cost effective approaches to reinstate forest on these landscapes. Assisted regeneration is a potentially lower cost restoration approach which aims to accelerate forest recovery by removing barriers to natural regeneration. However, despite being widely used its ecological benefits are poorly quantified, particularly on long cleared and grazed land. This study quantified the benefits of assisted regeneration on previously cleared land in a subtropical rainforest ecosystem within eastern Australia. Three different site types were used (grazed, grazing excluded and grazing excluded plus assisted regeneration) to compare forest recovery up to ten years after grazing was relieved with and without four to six years of assisted regeneration. Assisted regeneration sites showed a three-fold increase in canopy cover, four-fold increase in native tree and shrub species richness and over 40 times greater native stem density compared to non-assisted regeneration sites.

Stimulation of native recruitment appears dependent on the simultaneous removal of multiple barriers to regeneration, with the exclusion of grazing alone insufficient. This demonstrates the additional ecological benefits arising from investment in assisted regeneration. It offers considerable promise as a cost-effective tool for accelerating and improving re-instatement of forest on retired agro-pastoral land in the humid subtropics.

Keywords: assisted regeneration, native recruitment, forest recovery, canopy cover, agro-pastoral land
Introduction
Since the early 19th century deforestation of tropical forests and other biomes has occurred at an alarming rate with more than one-third of ecosystems converted for human use (Suding 2011; Paul et al. 2010). Socio-economic shifts (e.g. urbanization) and agro-economic marginality have contributed to the abandonment of considerable areas of agro-pastoral land, but residual vegetation remains fragmented with ongoing potential for biodiversity loss (Sobanski & Marques 2014; Sloan et al. 2015). Ecological restoration is an increasingly important tool used to mitigate human damage and achieve a diverse range of conservation outcomes (McBride et al. 2010). Globally over 150 million ha of disturbed and degraded land has been targeted to be restored by 2020 (Menz et al. 2013).

A major impediment to landscape-level restoration is financial cost (Parrotta et al. 1997) and so there is a need to identify cost-effective restoration techniques. Restoration interventions can vary along a spectrum from passive to active (Holl & Aide 2011). A highly passive approach is focused on natural or unassisted regeneration and is usually considered on degraded land in which recovery is likely within a set time-frame (Van Andel & Aronson 2006). Highly active approaches include planting or seeding to reintroduce native species or restoring the topography of terrestrial and wetland systems (Perrow & Davy 2002; Van Andel & Aronson 2006). This can yield rapid benefits but is often expensive (Catteral & Harrison 2006) and the scalability of such methods over large areas is often questioned (Prach & Hobbs 2008; Clewell & McDonald 2009). More appropriate for this site is a third, intermediate, strategy between natural regeneration and active reconstruction. This strategy is commonly termed assisted regeneration (Standards Reference Group SERA 2017). This approach aims to accelerate natural regeneration by removing barriers to it, which typically include competition from non-native plants and recurring disturbances such as grazing, harvesting and fire (Shono et al. 2007). Assisted regeneration is potentially more cost effective than active approaches because planting and seeding costs are eliminated (Ganz & Durst 2003). In Australia assisted regeneration is typically used in the context of bush or rainforest regeneration in which grazing is alleviated and herbicide control of non-native plants carried out (e.g. Woodford 2000; Harden et al. 2004).
However, despite an obvious demand for lower cost interventions and the widespread application of assisted regeneration within a range of degraded land types globally, there have been relatively few studies quantifying its actual benefit (but see Caradang et al. 2007). Furthermore there is a paucity of studies on the applicability of assisted regeneration on long cleared and grazed land in Australia such as retired agro-pastoral land, although the effect of distance from extant vegetation on natural recovery has long been understood (McClanahan 1986, Cairns 1991, Dosch et al. 2007). These information gaps can impede effective decision-making regarding the appropriate choice of restoration approaches that differ in cost, labour resources and recovery rates (Shoo et al. in press). Additionally, restoration of retired agro-pastoral land remains a key challenge, notorious for its variable rate of natural recovery and optimal restoration approaches of such areas are not yet completely understood (Shoo & Catterall 2013). Currently lacking is a quantitative understanding of the extent to which removing grazing (often a first step) and the subsequent application of assisted regeneration influences the rate of forest recovery under different contexts (e.g. vegetation quality, weed species). This represents a fertile area of applied research that can provide useful information about contexts where assisted regeneration management strategies might be most applicable.

This study aims to compare the potential of two levels of management intervention to restore structure and recruitment of the tree and shrub community on retired agro-pastoral land: 1) exclusion from grazing; and 2) exclusion from grazing plus the application of assisted regeneration (in the form of herbicide treatment of non-native vegetation). Native recruitment and canopy cover were used to measure the degree of vegetation recovery that occurred ten years after grazing was relieved with and without an additional four to six years of assisted regeneration.

**Methods**

**Study Area**

The study was conducted within the Numinbah Conservation Area, Numinbah Valley, in southeast Queensland, Australia (28.0167° S, 153.4000° E). Numinbah Valley represents an important linkage between two areas of World Heritage listed Gondwana Rainforests of Australia on the Springbrook and Beechmont plateaus (GCCC 2009b). Settlement of the area in the 1870s was first associated with timber getting and later dairy, beef production and banana plantations (Hall et al. 1988).
Experimental Design
The experimental design consisted of three site types that were differentiated based on presence of ongoing disturbance (i.e. grazing) and level of restoration intervention. These were: grazed-only, ungrazed-only and ungrazed plus assisted regeneration. All sites were previously subtropical rainforest historically cleared and subjected to grazing; but grazing was relieved in 2005 (ten years prior to study) from ungrazed-only and ungrazed-plus assisted regeneration sites. Ungrazed plus assisted regeneration sites also received assisted regeneration treatment in the four to six years prior to evaluation. Assisted regeneration consisted of systematic control of non-native plant species to encourage regeneration of native species using a range of techniques: cut, scrape and paint with herbicide in close proximity to native plants; over-spraying herbicide after isolating infestations; spot spraying herbicide when germination or reshooting occurred; and, manual removal on steep banks and near sensitive plants (D. Roche pers. comm.). Non-native species were continually suppressed to ensure native species germinated and grew to a point where most vegetation gaps had been filled with native species.

Five replicate sites were established for each of the three site types (see Fig. 1 for an overview of sites), all within the same pre-clear regional ecosystem classified as complex notophyll vine forest on Cainozoic igneous rocks, with an elevation < 600m (RE 12.8.3). A combination of historical aerial photography, spatial maps of pre-clearing and current vegetation and spatial mapping of annual restoration work by the local government authority, along with pre-existing site-level photo-point monitoring data (for three ungrazed assisted regeneration sites) were used to select and retrospectively characterise the baseline conditions of all sites (see Supplementary Material A).
Fig. 1. Aerial photograph (2011) showing the location of survey sites within the Numinbah Conservation Area. UT = Ungrazed Assisted Regeneration sites (N=5), UC = Ungrazed-only sites (N=5), GC = Grazed-only sites (N=5). Red line indicates the approximate position of the fence-line used to exclude grazing; white line, unpaved access road; green shading, pre-clear extent of regional ecosystem code 12.8.3 (complex notophyll vine forest on Cainozoic igneous rock).

In practice, potential confounding factors may mask a treatment’s effect and can inhibit a proper evaluation of conservation interventions (Ferraro & Pattanayak 2006). In forest recovery several factors, such as surrounding landscape, intrinsic resilience of the ecosystem, land use history and existing cover of trees and shrubs are known to potentially influence the rate of vegetation recovery (Holl 2007; Shono et al. 2007). Effort was made to standardise several potentially confounding factors (see Supplementary Material A for site selection criteria and descriptions of site types). For example, we specifically quantified and accounted for differences in initial cover of trees and shrubs by incorporating as a covariate in subsequent analyses (see below) and all selected sites were within close proximity (maximum distance 120 m) to remnant forest, although treatments were not specifically blocked for distance.
Field Methods

On-ground vegetation surveys were undertaken to quantify measures of vegetation development with a focus on canopy cover and native tree and shrub recruitment. Site centre points were located in the field using GPS and 50m transects were delineated at bearings previously established during site selection. Canopy cover was visually estimated as the percentage cover of trees and shrubs > 2m (native and non-native) above ground level in each of three 10m x 10m quadrats (centred at 5m, 25m and 45m along the transect).

Recruitment was evaluated by counting all live free-standing stems of trees and shrubs > 1m within 2.5 m either side of the transect (total area surveyed = 50m x 5m per site = 0.025 ha). All stems were identified to a species level and tallied by dbh class (<2.5cm, 2.5-5cm and 5-10cm). It was not considered necessary to extend the sampling protocol to accommodate large trees (of dbh > 10cm) as they were not part of this recruitment-focussed study. Instead, large trees were considered to represent relictual or regrowth ‘paddock’ trees (as opposed to evidence of recent recruitment). One to two paddock trees were recorded in a subset of sites within each of the site types (2, 2 and 3 sites in grazed-only, ungrazed-only and ungrazed plus assisted regeneration respectively).

Species belonging to other life-forms, including grasses, herbs and ferns (both typically clumped) and vines were recorded where present within any of the three quadrats.

Data Analysis

Individual observations were classified by life-form (tree/shrub, herb, vine, fern, grass/sedge), origin (native or non-native) and height (>1m or <1m). Although count data for three dbh classes (<2.5cm, 2.5cm-5cm, 5-10cm) were recorded separately, for the purpose of this analysis, these were grouped to a single dbh class (i.e. dbh <10cm).

Sites were replicates in statistical analyses (five replicates for each site type). Data for attributes that were subsampled within sites were pooled at the site level (i.e. canopy cover). Analysis of covariance (ANCOVA) was used to test for differences in vegetation attributes (stem density and species richness of recruited trees and shrubs) between site types (three-level factor) after accounting for variation in initial (2005) canopy cover.
Species richness and stem density analyses were repeated for all individuals, native individuals only and non-native individuals only. Prior to analysis, homogeneity of variances was evaluated using Bartlett’s test. Subsequently, stem density was log transformed to satisfy the assumption of homogeneity of variance and all analyses were performed on transformed data. Pair-wise comparisons amongst site types were performed using Tukey’s honest significant differences method (TukeyHSD function in R) at 95% confidence levels. Rarefaction was also used (Chao et al. 2014) to compare species richness–abundance relationships (details in Supplementary Material B).

Finally, dissimilarity in floristic composition of trees and shrubs (<10cm dbh) among site types was estimated using the Bray-Curtis index (based on whether species were shared between site pairs) and visualised using non-metric multi-dimensional scaling ordination via the metaMDS function in the R package vegan (Oksanen et al. 2013; Clarke & Ainsworth 1993). We used PerMANOVA to test for compositional differences among the three site types via the ‘adonis’ function in the R package vegan.

**Results**

**Structural attributes of vegetation**

**Aerial photography – temporal change in cover (both native and non-native trees and shrubs)**

In 2005 (the baseline year of this study), all sites had similar mean tree and shrub vegetation cover (15.13% for grazed-only sites, 17.13% for ungrazed-only and 15.66% for ungrazed assisted regeneration sites, F = 0.058, P < 0.944, Fig. 2). Ungrazed assisted regeneration sites showed the largest overall temporal gain in cover (reaching approximately 40% by year 8) and was particularly pronounced after year 4 when sites had commenced assisted regeneration. Cover at ungrazed-only sites exhibited a similar upturn (slightly over 10%) but this occurred later (i.e. between years 6 and 8) and accumulated cover by year 8 was a more modest at 30.5%. There was limited evidence of change at grazed-only sites where cover only increased by 5% over the 8 year time-span of aerial photography, reaching 20.1% (Fig. 2)
Fig. 2. Comparison of the estimated percentage cover of trees and shrubs > 2m (both native and non-native) between site types over 10 years (2005, 2009, 2011 and 2013 - all assessed by aerial photographs; and, 2015 - assessed in the field). Thin lines and open circles indicate mean of individual estimated site tree and shrub cover from three quadrats; bold lines, mean tree and shrub estimated cover across sites within each site type. Vertical arrows indicate onset of exclusion from grazing and horizontal arrow represents period of assisted regeneration.

Field Assessment

Mean canopy cover of native and non-native trees and shrubs (with height > 2m) differed among site types ($F = 11.72, P = 0.002$) and was highest at ungrazed assisted regeneration sites (51.4%) followed by ungrazed-only and grazed-only sites (17.7% and 16.3%, respectively) (Fig. 2). Pairwise analyses showed significant differences between ungrazed assisted regeneration and other site types (both $P < 0.004$). Though differences in methods prevent a direct comparison, the field-assessed mean canopy cover also appeared to represent a continued increase in tree and shrub cover from the aerial photo-assessed estimates (Fig. 2). In contrast, tree and shrub cover at both ungrazed-only and grazed-only site types actually decreased from year 8 mean values (Fig. 2). All grazed-only sites had considerable grass coverage (native and non-native were not distinguished) with a mean of almost 80%, principally Broad-leaved Paspalum (*Paspalum mandiocanum*). Ungrazed-only sites also had moderate grass cover with a mean of 39%, albeit with high variance. In contrast, all ungrazed assisted regeneration sites had very low grass cover (a mean of less than 1%).

Stem density

The survey obtained 713 records of tree and shrub stems (< 10cm dbh and > 1m in height). The vast majority (73.3%) of all stems were associated with ungrazed assisted regeneration sites of which 98% were native. Ungrazed-only sites comprised only 14.7% of counted tree
and shrub stems and most were non-native (92.7%). Grazed-only sites contributed 7.8% of stems of which 78.8% were non-native.

There were differences between site types in total, native and non-native stem density with no obvious effect of initial canopy cover (Table 1, Fig. 3). Pair-wise analyses revealed that: native stem density was greater in ungrazed assisted regeneration than other site types (both P < 0.006); non-native stem density was lower in ungrazed assisted regeneration than ungrazed-only (P = 0.040); and, total stem density was greater in ungrazed assisted regeneration than grazed-only (P = 0.009).

![Figure 3](image)

**Fig. 3.** Comparison of total, native and non-native stem density of trees and shrubs (< 10cm dbh and >1m in height) between site types. Open circles indicate site estimates; lines, mean estimate across sites within each site type.

**Floristic diversity and composition**

A total of 124 species were identified across all sites and comprised 72 trees and shrubs (58.1%), 27 herbaceous plants (21.8%), 6 grasses or sedges (4.8%), 10 vines (8.1%) and 9 ferns (7.3%). Most species of trees and shrubs, vines, ferns and grasses or sedges were classified as native (90.2%, 70%, 100% and 66.7%, respectively) but the percentage of native species was considerably lower for herbaceous plants (25.9%).
**Table 1:** The effect of site-type on vegetation attributes, using ANCOVA with initial canopy cover as a covariate.

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*All analyses of stem density were performed using log transformed data

**Species richness**

Total and native tree and shrub species richness (< 10cm dbh and > 1m in height) differed strongly between site types (Table 1, Fig. 4). Pair-wise analyses indicated that site-level differences were between ungrazed assisted regeneration sites and other site types (in all cases P < 0.001), coinciding with a 3-6 times greater species richness at ungrazed assisted regeneration sites (Fig. 4). Non-native species richness, in contrast, was comparatively much lower and did not differ between site types (Table 1, Fig. 4). Rarefied species richness showed that ungrazed assisted regeneration sites consistently had higher native tree and shrub species richness values for a given number of stems than both grazed-only and ungrazed-only sites indicating that species richness accumulated more rapidly in these sites (Fig. S3).

![Graph](image)

**Fig. 4.** Comparison of total, native and non-native species richness of trees and shrubs (< 10cm dbh and >1m in height) between site types. Open circles indicate site estimates; lines, mean estimate across sites within each site type.
**Composition**

Bray-Curtis dissimilarity analysis with PerMANOVA testing showed that the floristic composition of trees and shrubs (<10 cm dbh and >1m in height) differed strongly between site types. Ungrazed assisted regeneration sites were separated from all other sites while there was considerable overlap (similarity) between grazed-only and ungrazed-only sites (Fig. 5).

![Non-metric multi-dimensional scaling ordination plots](image)

**Fig. 5.** Non-metric multi-dimensional scaling ordination plots (based on Bray-Curtis dissimilarity) of the composition of native and non-native trees and shrubs (<10 cm dbh) between site types. Closed circles = grazed; open circles = ungrazed; open triangles = ungrazed plus assisted regeneration.

**Discussion**

Efforts were made to control for non-treatment factors that could potentially confound vegetation recovery. However, ungrazed assisted regeneration sites were, on average, 30m closer to remnant forest than both grazed and ungrazed sites. This greater proximity may have facilitated greater seed dispersal (Dosch et al. 2007) and explained some of the increased native recruitment seen in these sites.

However we consider the size of the differences cannot be explained by distance effects and suggest that the results demonstrate that additional investment in assisted regeneration can
considerably accelerate early forest recovery on retired pasture, well above what might be expected from simply removing disturbance alone (i.e. exclusion of grazing). Ungrazed assisted regeneration sites had approximately three times more canopy cover, four times greater native tree and shrub richness and over 40 times greater native stem density than grazed-only and ungrazed-only sites, indicating a clear ecological benefit over simply relieving grazing (ungrazed-only sites) or taking no restoration action at all (grazed-only sites). Additionally, the attributes of high grass cover and density of non-native shrubs that were characteristic of grazed-only and ungrazed-only sites, respectively, were not evident at ungrazed assisted regeneration sites. Differences between site types are considered in more detail below, along with possible underlying mechanisms and implications for future management decisions on similar degraded land.

*Status quo – ongoing grazing*

Sites that experienced ongoing grazing (grazed-only sites) showed limited evidence of development in forest attributes. Canopy cover remained very low, was coupled with extensive cover of pasture grasses (mostly non-native Broad-leaved Paspalum) and there was very little evidence of native tree and shrub recruitment. Whilst stocking levels were relatively low the presence of cattle can be expected to have contributed to seedling mortality, both directly (through consumption or trampling of seedlings) and indirectly (through compaction of soil and a subsequent reduction in infiltration rates) (Gageler et al. 2014, Posada et al. 2000). Grass cover has been cited as a principal limiting factor affecting native tree seedling survival and growth (Holl 1999, Hooper et al. 2005) and, given the extensive grass cover of grazed-only sites, this was likely also an important barrier.

*A modest benefit of relieving grazing*

There was little additional benefit evident from relieving grazing. Canopy cover remained similarly low at ungrazed-only sites with limited evidence of native tree or shrub recruitment. Cover of pasture grass was moderately reduced at some sites but remained high at other sites. However, the most prominent difference between grazed and ungrazed sites was the greater stem density of the non-native shrub Lantana (*Lantana camara*). Lantana is known to negatively impact the diversity and abundance of native species (Gooden et al. 2009, Sanders et al. 2003) and suppress native recruitment (Litton et al. 2006), especially in heavily infested areas (Fensham et al. 1994) and this appears a likely factor in low recruitment in ungrazed-only sites.
Despite these negative effects, the presence of Lantana may provide benefits to forest recovery not afforded by grass cover. As a flowering shrub, it significantly increases vegetation structure (compared to grasses) and so might be expected to attract seed-dispersing birds, ultimately accelerating (relative to grazed-only sites) the re-establishment of dispersal and seedbanks. As soil seed banks were not evaluated in this study, this can only be speculated upon, although it can be said that if any such effect existed it, did not translate to greater density of seedlings.

**Additional benefit of assisted regeneration**

In contrast, the results of the study suggest assisted regeneration facilitates successful native tree and shrub recruitment and can significantly accelerate the rate of forest recovery relative to grazed-only and ungrazed-only sites. Ungrazed assisted regeneration sites were characterised by much higher canopy cover (despite staged removal of non-native Tobacco Bush, *Solanum mauritianum*), greater native tree and shrub stem density, species richness and a shift in floristic composition toward a community dominated by native species, along with much lower grass cover. This indicates that many of the initial barriers to forest regeneration (i.e. competition with non-natives, seed dispersal limitation, seed germination and seedling survival) have been at least partially alleviated.

**Recovery of reference forest attributes**

After 10 years of exclusion from grazing with four to six years of assisted regeneration, ungrazed assisted regeneration sites had reached about two-thirds of canopy cover expected for reference forest (i.e. closed ~80% canopy cover) and native tree and shrub density was comparable to previous measurements of intact rainforest (i.e. over 3000 stems per hectare) (Kanowski et al. 2003; Shoo et al. 2015). A comparative assessment of species richness is more problematic with only young stems counted and inconsistencies in the size of area sampled among studies. However, the average of almost 12 native tree and shrub species at ungrazed assisted regeneration sites appears to be three to four times lower than species richness measurements of south-eastern subtropical rainforest communities (Laidlaw et al. 2011).

Stark differences also remained in the representation of species expected from reference forest. Of the 12 characteristic species listed for this regional ecosystem, only two were
present in ungrazed assisted regeneration sites with stems over 1m (and a dbh < 2.5cm); Native Olive (*Olea paniculata*) and Rose Marara (*Pseudoweinmannia lachnocarpa*), although when all stems (or seedlings) below 1m were taken into account three more of these species were present: White Bollygum (*Neolitsea dealbata*), Blackbean (*Castanospermum australe*) and Native Tamarind (*Diploglottis australis*).

**Implications for management**

The partial but incomplete canopy cover of ungrazed assisted regeneration suggests several important conditions have not yet been reached. Reformation of the canopy has been shown to be an important milestone in forest recovery, allowing for the microclimate on the forest floor to stabilize, in turn improving conditions for the germination and survival of shade-loving rainforest species (Harden et al. 2004). The canopy gaps of ungrazed assisted regeneration sites provide sunlight for opportunistic grasses and herbs and increase the likelihood of these in the seed bank (Paul et al. 2010). A strong negative relationship in canopy cover of the upper story and lantana density in dry rainforest (Fensham et al. 1994) also suggests the possibility of Lantana re-establishment. This demonstrates a maintenance phase has not yet been achieved and that ungrazed assisted regeneration sites require ongoing assisted regeneration (such as spot-spraying of newly germinating and re-sprouting non-natives).

**Conclusions**

A varied array of factors can influence recovery and a notable design limitation was the greater proximity to remnant forest of ungrazed assisted regeneration. Despite this, there is strong support for the applicability of assisted regeneration on retired agro-pastoral land, with a trajectory of accelerated recovery clearly evident and recovery of some forest attributes appearing achievable relatively quickly (within ten years). Importantly, the exclusion of grazing alone does not appear to facilitate successful recruitment of native trees and shrubs in the short-term, supporting assertions that it is necessary to simultaneously remove multiple barriers to promote forest recovery (Shoo & Catterall 2013). Together, assisted regeneration shows considerable promise as a cost-effective tool for improving the ecological value of retired agro-pastoral land and secondary forest in the humid subtropics.
References


