Biogeosciences Discuss., 9, 18545–18569, 2012
www.biogeosciences-discuss.net/9/18545/2012/
doi:10.5194/bgd-9-18545-2012

Biogeosciences
Discussions

Climate suitability estimates offer insight into fundamental revegetation challenges among post-mining rehabilitated landscapes in eastern Australia

P. Audet[1], **S. Arnold**[1], **A. M. Lechner**[1,2], **D. R. Mulligan**[1], **and T. Baumgartl**[1]

[1]Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia
[2]Centre for Environment, The University of Tasmania, Hobart, Australia

Received: 11 December 2012 – Accepted: 11 December 2012
– Published: 18 December 2012

Correspondence to: P. Audet (p.audet@uq.edu.au), S. Arnold (s.arnold@uq.edu.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Rehabilitation of post-mining sites in semi-arid/subtropical environments of eastern Australia have a general objective to establish specific types of native vegetation communities as defined in mine closure plans and in relation to the specific biotic and abiotic requirements of such communities. Critical for the success of rehabilitation is the availability of water and hence the climatic characteristic of this geographical region which is defined by a number of weather-bound factors (e.g. potentially erratic rainfall and periods of drought and flooding). However, specific estimates of climate suitability are seldom incorporated into current mined land rehabilitation design. To address this, our analysis combined various broad-scale climatic parameters (i.e. primarily relating to rainfall) to assess bioregional suitability-susceptibility within the context of plant early-establishment in the objective of informing rehabilitation schemes as to the inherent environmental challenges influencing both short- and long-term ecological development. Following our survey of available climate data, we derived site suitability-susceptibility indexes (that are otherwise currently not available within rehabilitation schemes) and compared the performance of 9 mine site locations in which our Centre has been engaged in environmental monitoring (Weipa, Mt. Isa, Ernest Henry, Eromanga, Kidston, Curragh, Tarong, North Stradbroke Island, and Newnes Plateau). More specifically, the sites were ranked from most-to-least suitable and compared with natural vegetation patterns (as estimated by the mean NDVI). Overall, it was determined that regular rainfall and relatively short periods of water-deficit are key characteristics of climate suitability (as found among the relatively more temperate coastal-hinterland sites), whereas high rainfall variability and (or) prolonged seasonal drought are primary characteristics of unsuitability (as found among the arid central-inland sites). Conceptual and practical considerations are provided which could inform rehabilitation schemes as to the inherent environmental challenges influencing both short- and long-term ecological development.

1 Introduction

In Australia (as elsewhere worldwide), a legislative requirement of highly assertive anthropogenic activities such as mining is the rehabilitation of affected landscapes to provide safe, stable, and self-sustaining post-disturbance environments (DEHP, 2012; DRET, 2006). When possible, rehabilitation schemes commonly aim toward the reinstatement of native plant communities indicative of pre-disturbance conditions; meanwhile, rehabilitation "success" is typically defined by the establishment of suitable levels of revegetation (both in terms of ecological structure and biodiversity) in relation to surrounding natural analogues (Bell, 2001; Bradshaw, 1997). Given the hierarchical nature of landscape complexity (Green and Sadedin, 2005), highly disturbed post-mining landscapes often require extensive and costly reconstruction of fundamental abiotic landform elements[1] as a critical first-step in rehabilitation prior to addressing any further aspects of ecological biological composition (Bergen et al., 2001). As a result, some post-mining ecosystems have been shown to display unforseen divergences in the development of the rehabilitated environments despite careful measures devised to achieve essential levels of functionality. Here, the (in)ability to achieve an intended "restoration" outcome is frequently attributed to the differences between the physico-chemical starting point of the post-disturbance environment compared to that of the intended post-rehabilitation outcome (Doley et al., 2012). Adding to these circumstances, an emerging scenario (which was first derived within the context of climate change potentially altering ecological boundaries) suggests that the suitability of climatic factors should represent a primary criterion predetermining the success or failure of initial vegetation establishment among many disturbed ecosystems (Harris et al., 2006; Hobbs et al., 2009; Jones et al., 2012). In our experience, specific estimates of climate suitability are seldom incorporated into current mined land rehabilitation design; yet, we suspect that the regional intensity, seasonality, and extremity of climate should represent

---

[1] E.g. referring to the texture, shape, and location of topographical features, or the seasonality and permanence of water bodies (Tongway and Ludwig, 2011).

an overarching and inextricably interwoven component of landscape complexity which influences the development of post-disturbance ecosystems. In cases where climate factors are taken into consideration, the selected parameters (e.g. typically surrounding mean annually rainfall) tend to over-simplify any assessment of regional climate suitability. For these reasons, this analysis seeks to assess various climatic parameters primarily relating to rainfall that are relevant to rehabilitation development (particularly plant early-establishment) and to compare these combined criteria across different geographic locations currently affected by ongoing mining activities. Overall, the manner in which these climatic factors are identified and ultimately addressed by land managers and rehabilitation practitioners could be a key determinate of rehabilitation success.

The Australian context for post-mining land rehabilitation provides a unique backdrop for examining the effects of climate suitability on the potential trajectories of post-disturbance landscapes (Tibbett et al., 2012). Australia holds an astonishing array of regional ecosystems (e.g. spread across equatorial, tropical and subtropical, desert, grassland, and temperate environments) having a diversity of flora and fauna deemed to be mega-diverse and containing biodiversity hotspots of international significance (Williams et al., 2002; Myers et al., 2000). More significantly, it also holds vast mineral and metal resources and has an economic dependance on mining and mineral processing (particularly coal, iron ore, and bauxite – among others) resulting in a range of anthropogenically disturbed landscapes. Unlike most temperate ecosystems, the rehabilitation of these affected landscapes is often complicated by weather-bound factors (e.g. potentially erratic rainfall and periods of drought and flooding) which can cause further challenges for rehabilitation schemes (e.g. dryland salinity and rapid degradation of soil fertility) (Williams et al., 2002). Following our survey of available climate data, we derived site suitability-susceptibility indexes (that are otherwise currently not available) for the assessment of the factors which influence early-establishment success and compared the performance of these indices among 9 mine sites in which our Centre has been engaged in environmental monitoring. And so, a key objective of this analysis is to emphasise notions of climate suitability as an early assessment tool to better account for potential rehabilitation successes or failures among these ecosystems.

2 Materials and methods

2.1 Site selection and climate data

Based on over 20 yr of working collaborations with mining industry partners, the Centre for Mined Land Rehabilitation (CMLR) has held a strategic and well-positioned perspective for assessing revegetation trends and challenges throughout the eastern Australian states of Queensland and New South Wales. Hence, sites considered in our analysis (i.e. Weipa, Mt. Isa, Ernest Henry, Eromanga, Kidston, Curragh, Tarong, North Stradbroke Island, and Newnes Plateau – Fig. 1) were selected on the basis of being locations for extensive mining activities which are also currently under investigation for environmental monitoring purposes by the CMLR. Under this pretext, each site had undergone and (or) will soon undergo significant post-mining land rehabilitation (relative to the size of the disturbance impact and deviation from the "original" system) toward the re-establishment of self-sustaining natural vegetation communities. In addition to our ongoing field-level familiarity with these disturbed ecosystems, the collective sites also provided an appropriate range of geo-climatic conditions (e.g. "dryness/wetness", periodicity, extremity/intensity) for examining climate parameters across eastern Australia and then comparing suitability-susceptibility criteria relevant to the early establishment of native vegetation (i.e. early succession systems). A summary of the site specific climatic zones and predominant vegetation classifications is shown (Table 1) according to IBRA 7 (2012) and Williams et al. (2002). Climate data were collected from and made available in the public domain by the Bureau of Meteorology (Government of Australia) (Bureau of Meteorology, 2012a). As described (below) in further detail, the primary data parameters included mean monthly temperature (°C), mean annual rainfall depth (mm yr^{-1}) and intensity (mm day^{-1}) based on daily rainfall, relative number of days (% yr^{-1}) with rainfall events > 25 mm and, likewise, < 3 mm, and median period (# days) without rain along with its standard deviation – as well as the length of the data capture. These long-term data were collected from weather stations nearest to the given mine sites and having the closest climatic similarity to these locations.

2.2 Rainfall metrics and climate suitability analyses

Each of the sites' climate parameters was scored qualitatively – i.e. being either highly suitable (ideal), moderately suitable (adequate), or unsuitable (susceptible) – in relation to a series of rainfall criteria (Table 2) which also included a description of the given parameter's indication of biological significance. These criteria and range values were selected according to a review of the literature and expert opinion based on available agricultural and environmental management assessments to provide arbitrary classification thresholds relevant to both short- and long-term vegetation development (derived according to DERM, 2010, and Fraser et al., 2010). For example, total annual rainfall and daily rainfall intensity were deemed to be indicators of the sites' general level of water availability, and the latter would also indicate erosion problems if intensity was too high. Likewise, the median period without rain (or water-deficit) and standard deviation for this period were indicators of water limitation and variability (i.e. the degree to which rainfall events were either regular or erratic). The % number of days per year with rainfall events > 25 mm are classified as high intensity rainfall events, whereas the % number of days per year with rainfall events < 3 mm rain were indicators of low intensity (i.e. non-disruptive) regular water supply. From these criteria, a quantitative suitability index (SI) was determined based on the sum of both highly (S_h) and moderately (S_m) suitable criteria per site. Conversely, a susceptibility index (SP) was determined based on the sum of unsuitable criteria. These values were then combined to determine an aggregated and later weighted index as defined by:

$$\mathrm{SI}_1 = S_\mathrm{h} + S_\mathrm{m} - \mathrm{SP}, \tag{1}$$

$$\mathrm{SI}_2 = 2S_\mathrm{h} + S_\mathrm{m} - \mathrm{SP}, \tag{2}$$

$$\mathrm{SI}_3 = S_\mathrm{h} + S_\mathrm{m} - 2\mathrm{SP}, \tag{3}$$

$$\mathrm{SI}_4 = 2S_\mathrm{h} + S_\mathrm{m} - 2\mathrm{SP}. \tag{4}$$

Data were then plotted in ascending/descending order of the site index values which ultimately corresponded to the same order across all analyses.

2.3 Remote sensing – estimates of vegetation density and rainfall

The relationship between the suitability-susceptibility indexes and natural vegetation patterns (or biogeographic regionalisation) was assessed using the remotely sensed "normalised difference vegetation index" (NDVI) which is commonly used as a spatial estimate of vegetation density and provides an arbitrary determinant of biozones and seasonal change (e.g. arid zones = low biomass and vegetation density; temperate zones = high biomass and vegetation density). NDVI values for two selected time periods and their associated coefficients of variation (NDVI-CV) were derived from the Global Inventory Modelling and Mapping Studies (GIMMS) data set (Pinzon et al., 2005; Tucker et al., 2005)[2]. Two one-year periods were chosen to represent extremes in climate found within Australia and each time period is represented as an aggregate of 24 scenes describing NDVI during an El Niño and La Niña Southern Oscillation period. These two extreme weather years were used to represent NDVI within the study rather than averaging the NDVI values for the complete data sets (1981 to 2006) in

---

[2] The GIMMS global data set is derived from imagery acquired from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17. It is available for a 25 yr period from 1981 to 2006 as bimonthly NDVI averages. The data set has been radiometrically corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change.

which the start and end dates are arbitrary in relation to weather conditions. The two events were chosen to represent the most recent of the 12 strongest El Niño and La Niña events identified in an analysis by Bureau of Meteorology (2012b, c) within the period where GIMMS data is available. The El Niño begun in April 1988 and the La Niña period begun in April 1997 Bureau of Meteorology (2012d, e). For each of the periods a whole year of data was captured, even though the El Niño/La Niña weather events did not last the entire period. This was to capture the seasonal trends in weather.

The average and the coefficient of variation (mean/standard deviation) were calculated for the two time periods. Site specific NDVI were then plotted against each of the rainfall metrics (described above) to determine the strength of correlation between each parameter. This was done to determine the most significant climatic/rainfall predictors of bioregional vegetation density, and which of the criteria were most well correlated with long-term/broad-scale vegetation development. All of the Spearman nonparametric correlation coefficients (r), degrees of freedom (df), and p-value estimates were calculated using SigmaPlot for Windows v. 12.0 (Systat Software Inc., San Jose, USA).

3 Results

A summary of all site-specific rainfall metrics used in our analyses is shown (Table 3); values deemed to be highly suitable (i.e. (ideal)) or unsuitable (i.e. (susceptible)) according to the suitability-susceptibility criteria are highlighted (as defined in Table 2). On their own, there were no clearly defined data trends regarding the incidence of highly vs. moderately suitable criteria among the sites (Fig. 2a). Yet, when combined, the final suitability index incorporating both (ideal) and (adequate) values indicated a clear pattern across all analyses whereby the relatively more temperate central-coastal sites (such as Tarong, Newnes Plateau, N. Stradbroke Island and Curragh) had more favourable rainfall criteria than the central-inland sites. Conversely, the susceptibility index (Fig. 2b) showed the opposite trend whereby arid central-inland sites (Ernest Henry-Cloncurry, Mt. Isa and Eromanga) had more unsuitable criteria of rainfall events than coastal sites. Upon closer analysis of Table 3, it is apparent that site suitability was primarily linked to the regularity of water availability (e.g. annual and daily rainfall) whereas site susceptibility was linked to the propensity for drought and irregularity/seasonality of rainfall (e.g. $< 500\,\mathrm{mm\,yr^{-1}}$ and > 20 days per period without rainfall). That being said, Kidston and Weipa – which are located among the north-east wet/dry tropics and showed adequate annual/daily water availability – were consistently found to be intermediately suitable/susceptible due to their prominently seasonal wet/dry rainfall distribution. From these findings, the aggregated indexes (based on the combination of both suitability and susceptibility criteria – Fig. 2c) then provided a unifying value for these trends and various positive/negative weightings of (ideal) vs. (susceptible) values further emphasised the most/least favourable climate conditions among each site. Overall, the ranking of sites for all aggregated values (from least-to-most suitable, or most-to-least susceptible) was Cloncurry (Ernest Henry) < Mt. Isa < Eromanga < Kidston < Weipa < Newnes Plateau < N. Stradbroke Island < Curragh (Bowen Basin) < Tarong. Despite each site having very different mean annual and daily rainfall values, this order of sites also appeared to coincide with the general pattern of monthly rainfall seasonality (Fig. 1a–h). In this regard, Tarong, Curragh, N. Stradbroke Island and Newnes Plateau indicated more consistent rainfall availability across all months of the year, meanwhile Kidston, Weipa, Mt. Isa and Cloncurry indicated distinct periods of drought/water-deficit. Eromanga indicated no apparent rainfall seasonality, but had the lowest total rainfall among all parameters.

Spatial distribution of vegetation density (as estimated by mean NDVI) and seasonal change in vegetation (as estimated by NDVI coefficients of variation) across eastern Australia are shown for the two selected periods of climate extremes: the La Niña spanning April 1988 to March 1989 (Fig. 3a, b) and the El Niño spanning April 1997 to March 1998 (Fig. 3c, d). El Niño/La Niña–Southern Oscillation is a quasiperiodic climate pattern that occurs across the tropical Pacific Ocean approximately every five years. They cause extreme weather such as floods and droughts in many regions of the world. Whether during the wet La Niña or the dry El Niño periods, the mapping of NDVI values generally corresponded with the desert/semi-arid interior zones (including Eromanga, Mt. Isa and Cloncurry) having lower total vegetation density vs. the temperate/wet subtropical coast and highlands (Tarong, Newnes Plateau, N. Stradbroke Island and Curragh) and north-east wet/dry tropics (Weipa and Kidston) which indicated higher total vegetation density. Albeit inherently low across the entire region, seasonal change in biomass appeared to be most pronounced in the central-inland desert/semi-arid zone (e.g. Eromanga) especially during the La Niña period. From these spatial distribution maps, mean NDVI values were plotted in relation to each of the aggregated suitability-susceptibility indexes (Fig. 4) described above. Significant positive correlations were found for all weighted indexes according to Spearman's Rank test (Fig. 4a: $r = 0.69$, $p < 0.05$; Fig. 4b: $r = 0.78$, $p < 0.01$; Fig. 4c: $r = 0.69$, $p < 0.05$; Fig. 4d: $r = 0.70$, $p < 0.05$). When plotted in relation to CV-NDVI, the aggregated suitability-susceptibility indexes showed no such correlations (data not shown) suggesting that these indexes were stable/constant in relation to seasonal changes (i.e. even in regions of high rainfall seasonality, variation in rainfall did not result in significant annual changes in NDVI). Lastly, the individual rainfall parameters used throughout all of the analyses are also plotted in relation to mean NDVI to determine the climate metrics most strongly correlated with natural vegetation patterns (Fig. 4, précis). Here, only the (R_d) mean annual rainfall showed a significant positive correlation (Fig. 4a – $r = 0.75$, $p < 0.025$), whereas the (R_0) median period without rain (Fig. 4f – $r = -0.84$, $p < 0.001$) and (${}_\mathrm{s}R_0$) standard deviation of period without rain (Fig. 4j – $r = -0.82$, $p < 0.001$) showed significant negative correlations. This outcome suggests that these three parameters were most closely related to the broad-scale natural/native vegetation density and total biomass across each bioregion, whereas the non-significant criteria (such as mean daily rainfall as well annual rainfall events > 25 mm and < 3 mm) were likely more closely related toward short-term vegetation development.

4 Discussion

Our study has demonstrated that a few common rainfall parameters (classified according to derived rainfall thresholds) can be combined in the form of indexes to interpolate bioregional climate suitability – criteria which are otherwise not currently available and (or) taken into consideration within the context of post-mining land rehabilitation. Given the accepted role that climate suitability factors should hold in predetermining the success or failure of initial vegetation establishment, particularly in this current era of climate change (Harris et al., 2006; Hobbs et al., 2009; Jones et al., 2012), a key aspect of this approach was that the selected rainfall parameters could represent potential indicators of both short- and long-term biological suitability or susceptibility within the context of post-disturbance ecological development (as described in Table 2). By comparing both the combined indexes and individual rainfall parameters with natural vegetation patterns (as estimated by the mean NDVI), we determined that the distribution of site suitability-susceptibility coincided closely with existing bioregional classification boundaries (summarised in Table 1) whereby the relatively more temperate coastal sites indicated greater suitability than arid central-inland sites (Hutchinson et al., 2005; IBRA7 2012; Williams et al., 2002). For this reason, we consider that the product of our analyses (summarised in the form of aggregated indexes) could be applied as a preliminary site assessment for identifying some of the broad-scale climate boundaries potentially affecting revegetation schemes: an approach culminating in our current bioregional ranking (from least-to-most suitable or most-to-least susceptible) of post-mining sites across eastern Australia. Unlike many bioregional classification systems that are primarily based upon a few broad-scale climate criteria (e.g. IBRA 7, 2012), the incorporation of short-term rainfall parameters (which are not directly linked to mean NDVI) has provided greater resolution regarding key criteria which could either favour or hinder the early-establishment of plants (e.g. rainfall intensity, ir/regularity of water availability, and frequency of water-deficit) at the scale of finer ecological processes. As discussed in further detail (below), the formulation of any such preliminary assessments could represent a necessary first-step in support of future investigations or optimising strategies seeking to address finer-scaled effects associated with unfavourable climate conditions (e.g. referring to works by Fischer et al. (2012a,b) in this issue), such as erosion control, management of soil fertility and matrix structure, maintenance of seed/ling viability and survivorship, etc.

4.1 What criteria cause certain sites to be more or less suitable?

At its extremes, our bioregional ranking of climatic conditions for post-mining sites across eastern Australia has provided a rather predictable depiction of how broad-scale rainfall patterns can shape the suitability/susceptibility of arid central-inland vs. temperate coastal-hinterland locations. Evidently, regular rainfall and relatively short periods of water-deficit are common characteristics of climate suitability, whereas high rainfall variability and (or) prolonged seasonal drought are primary characteristics of susceptibility; particularly regarding the early-establishment of plants among post-disturbance ecosystems. These fundamental relationships can be illustrated conceptually in our climate suitability/susceptibility matrix (Fig. 5a) which identifies a range of climate scenarios (including moderately suitable outcomes) in relation to the combined effects of differential rainfall availability and seasonal variation. That being said, our onsite experience (albeit anecdotal due to differences in site-specific metrics used between each project) tends to support these suitability/susceptibility scenarios through ongoing environmental monitoring of the post-mining sites[3]. In regards to sites deemed most climate suitable such as Tarong, N. Stradbroke Isld., and Curragh (Gravina et al., 2011, 2012; McKenna and Baiquni, 2011), rehabilitation development has achieved sufficient levels of vegetation structure and stability over a seemingly short period of time (approx. 10–15 yr post-rehabilitation). In terms of biological significance, rainfall patterns in favour of relatively lower seasonal variation and fewer large vs. small

---

[3] Monitoring of the Newnes Plateau is still in its early stages, therefore long-term data collection was insufficient to assess ecological development at this time.

intensity events have corresponded to conditions conducive to the stabilisation of the growth substrate and early-establishment of plants. Under these relatively more temperate environmental conditions, climate does not appear to represent a significant abiotic threshold/boundary for ecological development. By contrast, rehabilitation development of central-inland sites deemed most susceptible, such as Mt. Isa, Ernest Henry (Cloncurry) and Eromanga, has indicated lower rates of vegetation establishment (even for native species that are well adapted to drought) and a propensity for seasonal flooding (Gravina and Grigg, 2004; Vickers et al., 2012). Here, the combination of seasonal periods without rainfall followed by high intensity rainfall events has contributed to a high risk of elevated runoff causing a sensitivity to erosion and loss/leaching of topsoil fertility, and thereby representing a significant abiotic impediment to vegetation establishment. Similar patterns of site susceptibility are also found for intermediately classified locations, such as tropical Weipa and Kidston, which indicated adequate water availability yet highly pronounced seasonal rainfall (Fig. 1a, d). In this case, intensive soil stabilisation/drainage and irrigation were required to achieve adequate revegetation levels (Bao et al., 2012; Gravina and Grigg, 2007). And so, even in cases when annual rainfall is adequate, the seasonal intensity of rainfall patterns can have severe consequences for rehabilitation development over the short-term.

4.2 Considerations for initial establishment strategies

A main consideration of our analysis is that the regional intensity, seasonality, and extremity of climate should represent a primary determinant of rehabilitation success among post-disturbance landscapes. Based on the common rainfall criteria used here, the strategy of identifying the initial site suitability and rainfall availability could be readily applied to other locations which are similarly affected by climate/rainfall extremes and used to guide rehabilitation planning – while adding no significant additional costs to rehabilitation design. Rehabilitation expectations for sites within different climatic zones and the amount of investment required for rehabilitation should be driven by an understanding of these general notions of climatic susceptiblity. Since these components are generally lacking from most planning assessments, we believe that our current study can represent a necessary starting point for further experimental investigations which could then feedback and improve upon current monitoring activities (such as bioregional climate and vegetation modelling). Although it would be imprudent to make site-specific recommendations concerning land-management strategies based only on such broad-scale classifications, the determination of climate suitability should still provide value-added for describing potential abiotic boundaries affecting ecological development and a generalised prognosis for rehabilitation development (Fig. 5b). For example, in cases of high climate unsuitability, rehabilitation planning could identify a need for extended commitments to rehabilitation through intensive monitoring of ecological performance and (when required) progressive land management. This could include pre-emptive mitigation strategies applied to overcome abiotic barriers of unsuitability such as soil-cover designs that trigger water availability. For instance, deep soils and low compaction to increase water holding capacity; or, silty/clayey soils to increase plant available water. Likewise, landform designs that minimise the effects of highly impactful rainfall events. For instance, gentle slopes to minimise runoff and facilitate infiltration and minimise erosion; or, Southern aspect design to minimise evapotranspiration. By extension, these rather simple and precautionary design considerations could hold significant implications, for example, when attempting to maintain seed viability during unfavourable climate conditions and later reducing ecophysiological stress/strain on seedlings to facilitate the stabilisation of the soil's matrix structure. Nevertheless, the effective identification of potential climate challenges should represent a critical step for identifying suitable ecological management strategies and thereby avoiding potentially divergent and (or) unproductive rehabilitation outcomes – particularly during the highly dynamic and initial phases of early-ecosystem development.

Acknowledgements. This study was made possible by postdoctoral fellowship schemes and early-career research funding from the Centre for Mined Land Rehabilitation and The University of Queensland in support of PA, SA, and AL.

References

Bao, N., Lechner, A., Fletcher, A., Erskine, P., Mulligan, D., and Bai, Z.: Spoting long-term changes in vegetation over short-term variability, International Journal of Mining, Reclamation and Environment, doi:10.1080/17480930.2012.710505, 2012.

Bell, L. C.: Establishment of native ecosystems after mining – Australian experience across diverse biogeographic zones, Ecol. Eng., 17, 179–186, doi:10.1016/S0925-8574(00)00157-9, 2001.

Bergen, S. D., Bolton, S. M., and Fridley, J. L.: Design principles for ecological engineering, Ecol. Eng., 18, 201–210, 2001.

Bradshaw, A.: Restoration of mined lands-using natural processes, Ecol. Eng., 8, 255–269, doi:10.1016/s0925-8574(97)00022-0, 1997.

Bureau of Meteorology: Climate data, available at: http://www.bom.gov.au/climate/data/?ref=ftr, last access: 19 November 2012a.

Bureau of Meteorology: Australian rainfall patterns during El Niño events, Australian Government, available at: http://www.bom.gov.au/climate/enso/ninocomp.shtml, last access: 19 November 2012b.

Bureau of Meteorology: Australian rainfall patterns during La Niñ a events, Australian Government, available at: http://www.bom.gov.au/climate/enso/ninocomp.shtml, last access: 19 November 2012c.

Bureau of Meteorology: El Niño – Detailed Australian Analysis, Australian Government, available at: http://www.bom.gov.au/climate/enso/enlist/, last access: 19 November 2012d.

Bureau of Meteorology: La Niña – Detailed Australian Analysis, Australian Government, available at: http://www.bom.gov.au/climate/enso/enlist/, last access: 19 November 2012e.

DEHP: Guideline Mining – Rehabilitation requirements for mining projects, Department of Environment and Heritage Protection, Queensland Government, available at: http://www.ehp.qld.gov.au/, last access: 11 December 2012.

DERM: Protecting Queensland's strategic cropping land: A policy framework. Department of Environment and Resource Management, Queensland Government, available at: http://www.derm.qld.gov.au/land/planning/pdf/strategic-cropping/strategic-cropping-policy-complete.pdf, last access: 19 November 2010.

Doley, D., Audet, P., and Mulligan, D. R.: Examining the Australian context for post-mined land rehabilitation: reconciling a paradigm for the development of natural and novel ecosystems among post-disturbance landscapes, Agr. Ecosyst. Environ., 163, 85–93, doi:10.1016/j.agee.2012.04.022, 2012.

DRET: Mine Closure and Completion, Leading Practice Sustainable Development Program for the Mining Industry, Department of Resources, Energy and Tourism, available at: http://www.ret.gov.au/resources/resources_programs/lpsdpmining/handbooks/Pages/default.aspx, last access: 19 November 2006.

Fischer, T., Veste, M., Bens, O., and Hüttl, R. F.: Dew formation on the surface of biological soil crusts in central European sand ecosystems, Biogeosciences, 9, 4621–4628, doi:10.5194/bg-9-4621-2012, 2012a.

Fischer, T., Yair, A., and Veste, M.: Microstructure and hydraulic properties of biological soil crusts on sand dunes: a comparison between arid and temperate climates, Biogeosciences Discuss., 9, 12711–12734, doi:10.5194/bgd-9-12711-2012, 2012b.

Fraser, G. W., Day, K. A., Carter, J. O., and McKeon, G. M.: Rain on the rangelands: how intense is it?, in: Proceedings of the 16th Biennial Conference of the Australian Rangeland Society, edited by: Eldridge, D. J. and Waters, C., Perth, 2010.

Gravina, A. and Grigg, A.: Mt. Isa mine rehabilitation monitoring 2004 assessment, Report to Mt. Isa Mines Ltd., The University of Queensland, Centre for Mined Land Rehabilitation, Brisbane, 82 pp., 2004.

Gravina, A. and Grigg, A.: Monitoring and assessment of rehabilitation for the closure of Kidston Gold Mine 2007 Assessment, Report to Kidston Gold Mine Ltd., The University of Queensland, Centre for Mined Land Rehabilitation, Brisbane, 82 pp., 2007.

Gravina, A., McKenna, P., and Glenn, V.: Evaluating the success of mineral sand mine rehabilitation on North Stradbroke Island, Queensland: Comparisons with reference Eucalypt communities, P. Roy. Soc. Queensland, 117, 419–436, 2011.

Gravina, A., Glenn, V., and Audet, P.: Tarong coal Meandu Mine and Kunioon test pit rehabilitation monitoring and compliance with EA criteria – 2011 Assessment, Report to Stanwell Corporation Ltd., The University of Queensland, Centre for Mined Land Rehabilitation, Brisbane, 98 pp., 2012.

Green, D. G. and Sadedin, S.: Interactions matter – complexity in landscapes and ecosystems, Ecol. Complex., 2, 117–130, doi:10.1016/j.ecocom.2004.11.006, 2005.

Harris, J. A., Hobbs, R. J., Higgs, E., and Aronson, J.: Ecological restoration and global climate change, Restor. Ecol., 14, 170–176, doi:10.1111/j.1526-100X.2006.00136.x, 2006.

Hobbs, R. J., Higgs, E., and Harris, J. A.: Novel ecosystems: implications for conservation and restoration, Trends Ecol. Evol., 24, 599–605, doi:10.1016/j.tree.2009.05.012, 2009.

IBRA 7: Interim Biogeographic Regionalisation for Australia, Australian Government Department of Sustainability, Environment, Water, Population and Communities, 2012.

Jones, H. P., Hole, D. G., and Zavaleta, E. S.: Harnessing nature to help people adapt to climate change, Nat. Clim. Change, 2, 504–509, 2012.

McKenna, P. and Baiquni, H.: Curragh coal mine rehabilitation monitoring 2010, Report to Wesfarmers Curragh Property Ltd., The University of Queensland, Centre for Mined Land Rehabilitation, Brisbane, 72 pp., 2011.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J.: Biodiversity hotspots for conservation priorities, Nature, 403, 853–858, 2000.

Pinzon, J. E., Brown, M. E., and Tucker, C. J.: Satellite time series correction of orbital drift artifacts using empirical mode decomposition, in: Hilbert–Huang Transform: Introduction and Applications, edited by: Huang, N. and Shen, S., World Scientific Publishing, Singapore, 167–186, 2005.

Tibbett, M., Mulligan, D., and Audet, P.: Recent advances in restoration ecology: examining the modern Australian agro-ecological and post-mining landscapes, Agr. Ecosyst. Environ., 163, 1–2, doi:10.1016/j.agee.2012.07.007, 2012.

Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, D. A., Pak, E. W., Mahoney, R., Vermote, E. F., and El Saleous, N.: An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data, Int. J. Remote Sens., 26, 4485–4498, doi:10.1080/01431160500168686, 2005.

Vickers, H., Gillespie, M., and Gravina, A.: Assessing the development of rehabilitated grasslands on post-mined landforms in north west Queensland, Australia, Agr. Ecosyst. Environ., 163, 72–84, doi:10.1016/j.agee.2012.05.024, 2012.

Williams, J., Hook, R. A., and Hamblin, A.: Agro-ecological regions of australia – methodologies for their derivation and key issues in resource management, CSIRO Land and Water, 88 pp., 2002.

Table 1. Biogeographic characteristics for each for each post-mining site.

Climate[a]	Major Vegetation Type[b]	Site Name	Location	Primary Commodity
Desert/ Semi-Arid Interior	**Scrub and Heathland**	**Eromanga**	**26° 40′11 S 143° 16′11 E**	**Oil and Gas**
Temperate Highlands	Shrubland and Swamps	Newnes Plateau	33° 28′23 S 150° 9′33 E	Coal
Wet Subtropical Coast	**Open-forest and Woodland**	**N. Stradbroke Island**	**27° 30′00 S 153° 25′00 E**	**Mineral Sands**
North-east Wet/ Dry Tropics	Tropical Shrubland and Savannah	Weipa	12° 37′44″ S 141° 52′44″ E	Bauxite
		Kidston	18° 52′46″ S 144° 9′12″ E	Gold
Semi-Arid Tropical/ Subtropical Plains	**Semi-Arid Woodland and Savannah Grassland**	**Mt. Isa**	**20° 44′ S 139° 30′ E**	**Lead, Silver, Copper, Zinc**
		Ernest Henry Mine	**20° 26′20 S 140° 42′47 E**	**Copper, Gold, Iron Ore**
Subtropical Slopes/ Plains	Humid Woodland	Curragh	23° 28′15 S 148° 53′15 E	Coal
		Tarong	26° 48′34 S 151° 54′13 E	Coal

[a] According to Williams et al. (2002) and Hutchinson et al. (2005).

[b] According to IBRA7 (2012).

Table 2. Rainfall parameters for climate suitability-susceptibility criteria and their biological significance.

Measure	Suitability criteria[a,b,c]			Indication of …
	Highly Suitable (Ideal)	Moderately Suitable (Adequate)	Unsuitable (Susceptible)	
R_d (mm yr^{-1})	> 1000	1000–500	< 500	Level of Water Availability (Co-Classifier Biogeographic Regionalisation)
R_i (mm day^{-1})	15–10	N/A	> 15; < 10	Daily Water Availability and Intensity (Sensitivity to Erosion)
$R_{\mathrm{d},25}$ (%)	< 10	10–20	> 20	Frequency of Intense Rainfall (Sensitivity to Erosion)
$R_{\mathrm{d},3}$ (%)	> 30	30–20	< 20	Frequency of Low-Intensity Rainfall (Non-Disruptive Water Supply)
R_0 (days)	< 5	5–10	> 10	Duration of Water Deficit (Water Limitation)
${}_\mathrm{s}R_0$ (days)	< 10	10–20	> 20	Ir/regularity of Water Deficit (Intensity of Water Limitation)

R_d: rainfall depth,
R_i: rainfall intensity,
$R_{\mathrm{d},25}$: Days of rainfall depth > 25 mm,
$R_{\mathrm{d},3}$: Days of rainfall depth < 3 mm,
R_0: median period with no rain,
${}_\mathrm{s}R_0$: standard deviation of period with no rain,

[a] DERM (2010).

[b] Fraser et al. (2010).

[c] IBRA7 (2012).

Table 3. Site-specific values of long-term rainfall parameters and vegetation density (NDVI).

Site Name	T_{obs} (yr)	R_{d} (mm yr^{-1})	R_{i} (mm day^{-1})	$R_{\mathrm{d,25}}$ (%)	$R_{\mathrm{d,3}}$ (%)	R_0 (days)	${}_{\mathrm{s}}R_0$ (days)	NDVI (NDVI-CV)	
								El Niño (1997–98)	La Niña (1988–89)
Ernest Henry	44	***476.1***	***16.98***	***33***	***0***	7	***37.7***	320 (0.3)	196 (0.1)
Mt. Isa	79	***429.3***	***9.8***	17	***0***	6	***25.7***	302 (0.1)	245 (0.1)
Eromanga	122	***267.8***	**11.65**	17	**33**	***13***	***30.3***	202 (0.2)	219 (0.3)
Kidston	87	704.7	***16.85***	20	20	**5**	***28.4***	454 (0.3)	487 (0.2)
Weipa	95	**1787.0**	***15.81***	***30***	25	**2**	13.6	431 (0.2)	389 (0.2)
Newnes Plateau	134	786.9	***4.78***	10	25	**2**	**3.3**	650 (0.1)	669 (0.2)
N. Stradbroke Island	57	**1603.8**	***16.15***	20	25	**4**	**6.4**	558 (0.1)	496 (0.2)
Bowen Basin	100	578.1	**13.38**	20	20	6	15.2	337 (0.3)	448 (0.2)
Tarong	15	656.4	**10.66**	13	**33**	**4**	**7**	680 (0.05)	626 (0.1)

T_{obs}: length of data set,
R_{d}: rainfall depth,
R_{i}: rainfall intensity,
$R_{\mathrm{d,25}}$: percentage of days with rainfall depth $>$ 25 mm,
$R_{\mathrm{d,3}}$: percentage of days with rainfall depth $<$ 3 mm,
R_0: median period of consecutive days with no rain,
${}_{\mathrm{s}}R_0$: standard deviation of period of consecutive days with no rain,
NDVI – Normalized difference vegetation index,
NDVI-CV – Coefficient of variation,
Values deemed to be "**highly suitable**" (ideal) and "***unsuitable***" (susceptible) are highlighted based on the suitability-susceptibility criteria (Table 2).

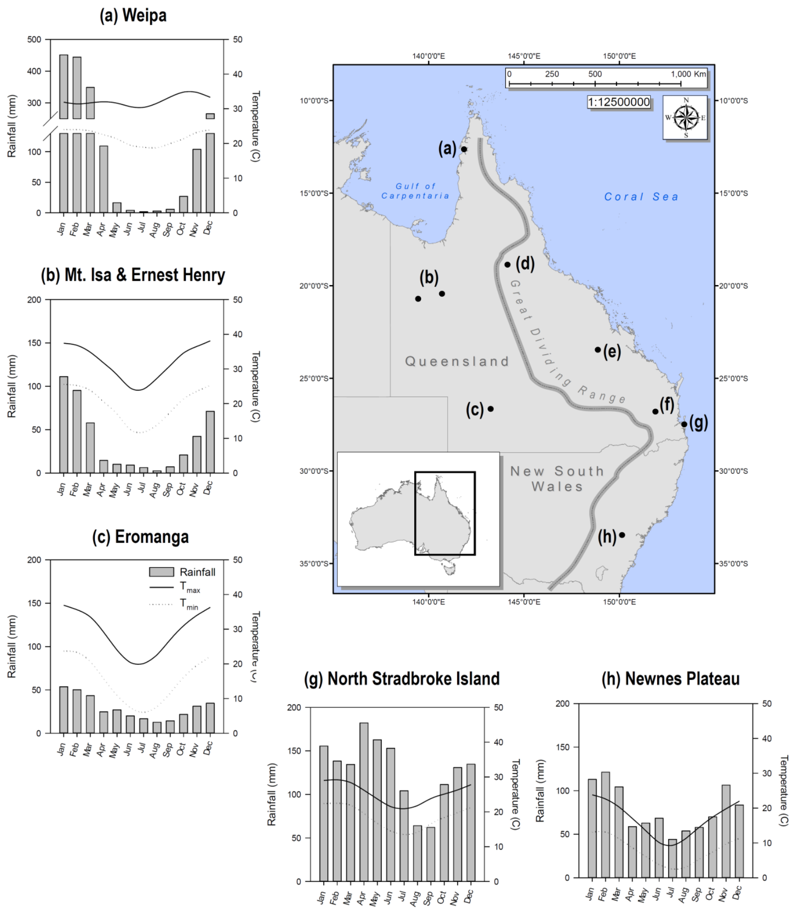


Fig. 1. Location and climate diagrams (average monthly temperature and rainfall) of rehabilitation sites considered for this study.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

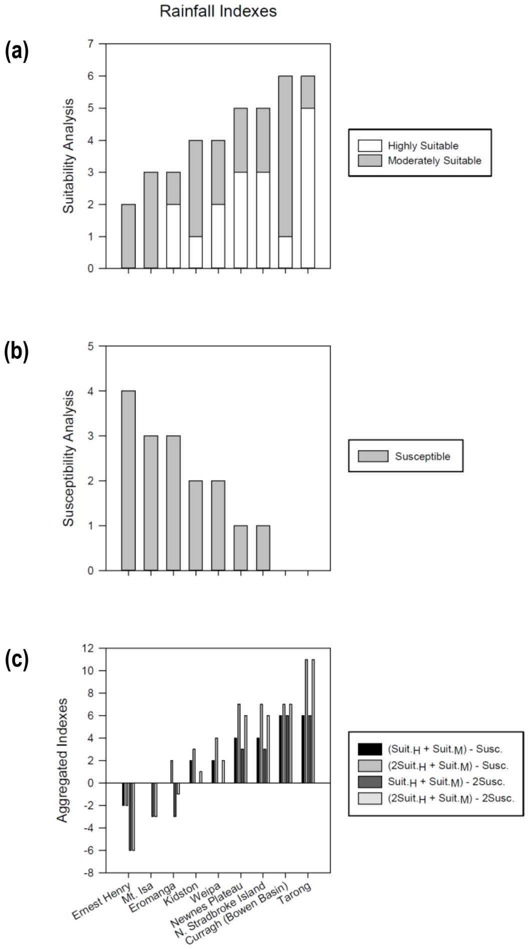


Fig. 2. Combined **(a)** highly (ideal) and moderately suitable (adequate) rainfall criteria, **(b)** susceptible (unsuitable) criteria, and **(c)** aggregated suitability index for each location.

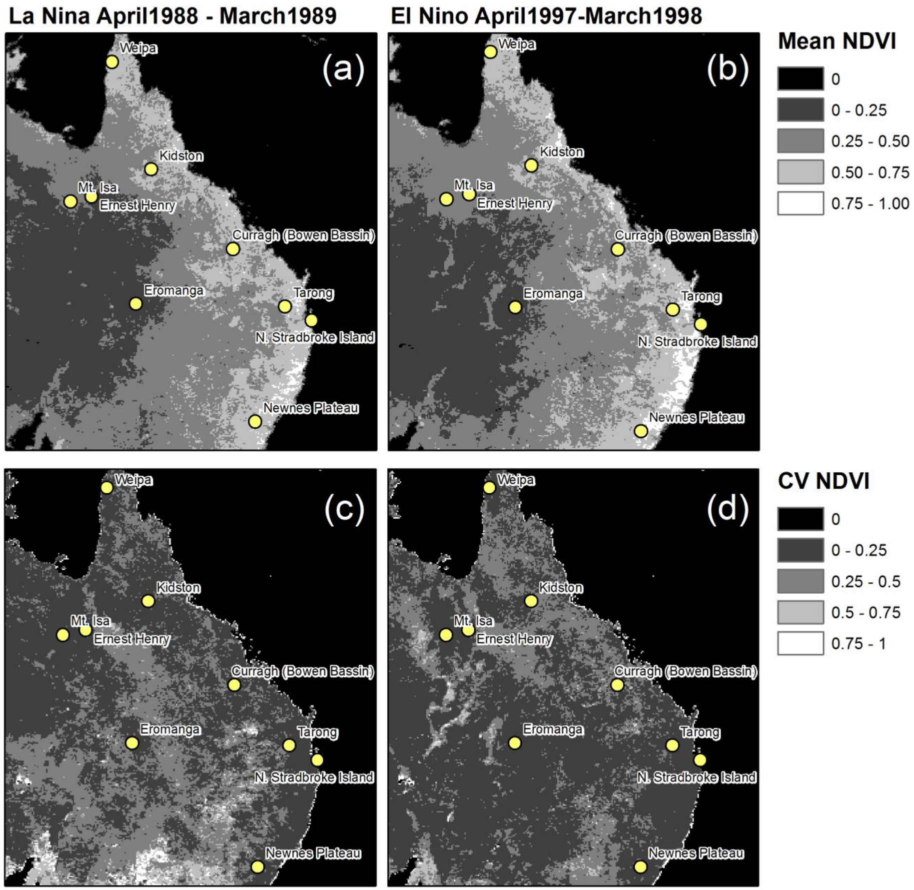


Fig. 3. Mean NDVI and coefficient of variation across eastern Australia for La Niña **(a, c)** and El Niño **(b, d)** climate periods.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

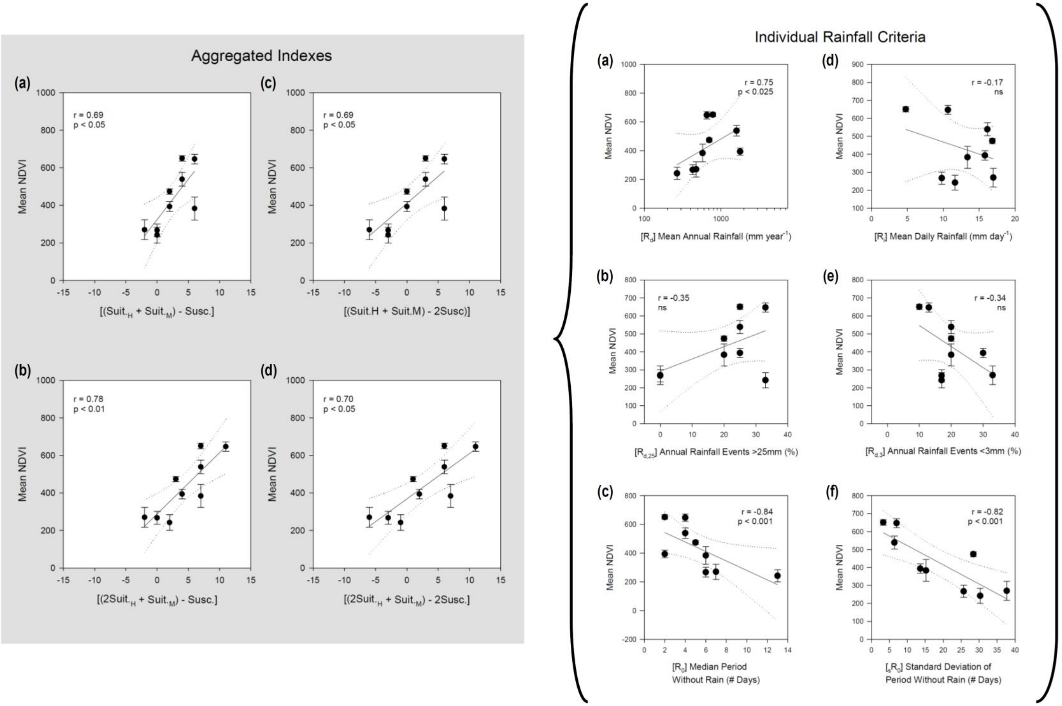
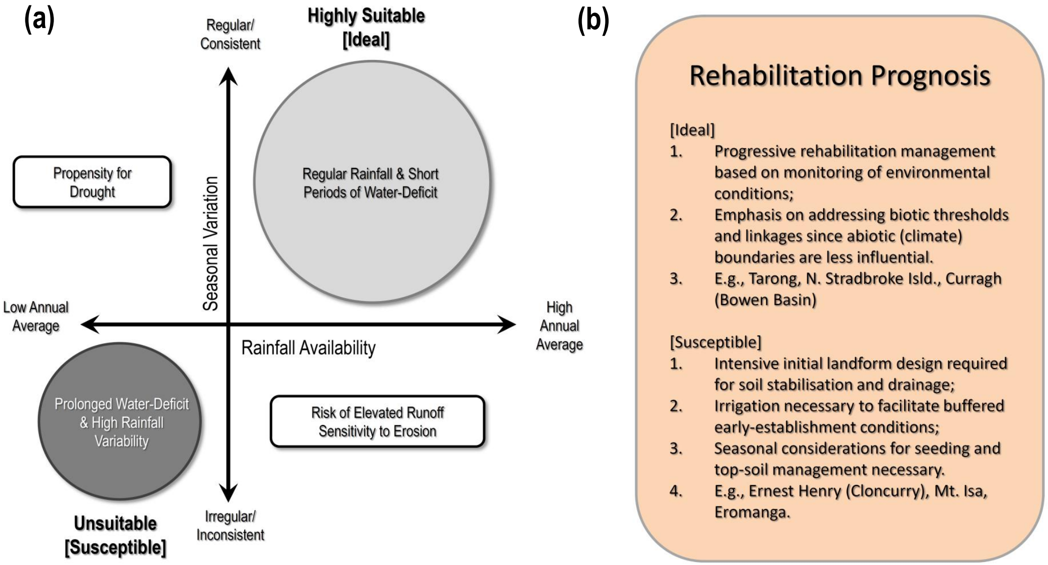


Fig. 4. Aggregated suitability indexes (shaded, **a–d**) and individual rainfall parameters (précis, **a–f**) in relation NDVI.



Rehabilitation Prognosis

[Ideal]

1. Progressive rehabilitation management based on monitoring of environmental conditions;
2. Emphasis on addressing biotic thresholds and linkages since abiotic (climate) boundaries are less influential.
3. E.g., Tarong, N. Stradbroke Isld., Curragh (Bowen Basin)

[Susceptible]

1. Intensive initial landform design required for soil stabilisation and drainage;
2. Irrigation necessary to facilitate buffered early-establishment conditions;
3. Seasonal considerations for seeding and top-soil management necessary.
4. E.g., Ernest Henry (Cloncurry), Mt. Isa, Eromanga.

Fig. 5. (a) Conceptual climate suitability matrix and **(b)** prognosis for rehabilitation development.