Severity-Duration-Frequency curves of droughts: An early risk assessment and planning tool for ecosystem establishment in post-mining landscapes

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Abstract

Eastern Australia has considerable mineral and energy resources and areas of high biodiversity value co-occurring over a broad range of agro-climatic environments. Lack of water is the primary abiotic stressor for (agro)ecosystems in many parts of Eastern Australia. In the context of mined land rehabilitation quantifying the severity-duration-frequency (SDF) of droughts is crucial for successful ecosystem rehabilitation to overcome challenges of early vegetation establishment and long-term ecosystem resilience.

The objective of this study was to quantify the SDF of short-term and long-term drought events of 11 selected locations across a broad range of agro-climatic environments in Eastern Australia by using three drought indices at different time scales: the Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI), and the Standardized Precipitation-Evapotranspiration Index (SPEI). Based on the indices we derived bivariate distribution functions of drought severity and duration, and estimated the recurrence intervals of drought events at different time scales. The correlation between the simple SPI and the more complex SPEI or RDI was stronger for the tropical and temperate locations than for the arid locations, indicating that SPEI or RDI can be replaced by SPI if evaporation plays a minor role for plant available water (tropics). Both short-term and long-term droughts were most severe and prolonged, and recurred most frequently in arid regions, but were relatively rare in tropical and temperate regions.

Our approach is similar to intensity-duration-frequency (IDF) analyses of rainfall, which are crucial for the design of hydraulic infrastructure. In this regard, we propose to apply SDF analyses of droughts to design ecosystem components in post-mining landscapes. Together with design rainfalls, design droughts should be used to assess rehabilitation strategies and ecological management based on drought recurrence intervals, thereby minimising the risk of failure of initial ecosystem establishment due to ignorance of fundamental abiotic and site-specific environmental barriers such as flood and drought events.

1 Introduction

Eastern Australia holds vast mineral and energy resources of economic importance and internationally significant biodiversity (Williams et al., 2002; Myers et al., 2000) occurring over a broad range of agro-climatic environments (Hutchinson et al., 2005; Woodhams et al., 2012). There are also extensive areas of cropping and grazing such as in the Brigalow Belt Bioregion (Arnold et al., 2013) and the wheatbelt regions around Kingaroy and Wagga Wagga (Woodhams et al., 2012) (Table 1, Fig. 1). Lack of water availability is a critical factor for the mining industry, agriculture and biodiversity. For example, water deficit reduces agricultural productivity and increases the risk of failure of ecosystem rehabilitation. Likewise, flooding affects mining as a result of soil erosion in rehabilitation areas or flooded mine workings preventing production. For some of the agro-climatic regions in Eastern Australia lack of water is the primary abiotic stressor for (agro)ecosystems throughout the year, whereas for others water availability is at least seasonally limited (Table 1). In the past century regions across Australia have regularly experienced periods of water deficit (Murphy and Timbal, 2008). These drought events are distributed diversely with regard to their duration, severity, and frequency of occurrence over the continent.

Droughts, and associated limitations in plant available water, determine plant distribution in response to climatic conditions in post mined lands. Ecosystem attributes are sensitive to the occurrence of drought events, for example the distribution of native tropical species (Engelbrecht et al., 2007; Kuster et al., 2013), the structure and functioning of forests (Zhang and Jia, 2013; Vargas et al., 2013), biodiversity and ecosystem resilience (Brouwers et al., 2013; Lloret, 2012; Jongen et al., 2013), and the primary productivity and respiration of vegetation (Shi et al., 2014). In the context of mined land rehabilitation, droughts also play a critical role for the early establishment of plants (Nefzaoui and Ben Salem, 2002; Gardner and Bell, 2007) and long-term resilience of novel (Doley et al., 2012; Doley and Audet, 2013) and/or native ecosystems on post-mining land (Bell, 2001). Across the life span of plants in early rehabilitation of post mined lands, due to their under-developed root system, juvenile vegetation such as seeds, seedlings, and pre-mature plants rather than climax vegetation are especially vulnerable to lacks of water availability (Jahantab et al., 2013; Craven et al., 2013; Arnold et al., 2014a). For climax vegetation, however, medium to long-term drought periods rather than short-term droughts may critically impact the post mined rehabilitation by altering plant communities' species composition (Mariotte et al., 2013; Ruffault et al., 2013).

Methods for characterising droughts vary in complexity depending on the climatic and environmental (e.g. soil moisture) factors considered. Meteorological or climatological droughts are the simplest and are based on the characterisation of anomalies in rainfall conditions (Anderegg et al., 2013). For meteorological droughts, standardised drought indices such as the Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI) and Standardized Precipitation-Evapotranspiration Index (SPEI) provide the foundation for quantifying the duration and severity, and eventually the frequency or recurrence of drought events (McKee et al., 1993; Tsakiris and Vangelis, 2005; Vicente-Serrano et al., 2010). These indices are commonly used to identify anomalies in rainfall patterns (Heim, 2002). As none of these indices apply universally to any climate region it is best for land managers to use a range of drought indices at various temporal scales (Heim, 2002; Spinoni et al., 2013). In many parts of the world evaporation data are unavailable or incomplete and simple rainfall indices are most commonly used. In this study we compare indices incorporating evaporation (SPEI and RDI) with the simple rainfall index SPI in order to determine the accuracy of using SPI across different climatic regions.

Drought periods can be characterised from a few hours (short-term) to millennia (long-term) depending on the ecological or socio-economic question being addressed. The time lag between the beginning of a period of water scarcity and its impact on socio-economic and/or environmental assets is referred to as the time scale of a drought (Vicente-Serrano et al., 2013). For example, for biochemists and molecular biologists the hourly time scale is of interest while geologists and palaeontologists operate in time scales of millennia. For meteorologists, farmers and agronomists monthly to yearly time scales tend to be of interest (Passioura, 2007). There are three time scales with which drought indices are usually calculated for: short-term droughts of less than three months; medium-term droughts between three to nine months and long-term droughts normally exceeding 12 months. Short-term droughts have an impact on water availability in the vadose zone (National Drought Mitigation Center, 2014; Zargar et al., 2011), while long-term droughts also affect surface and ground water resources (National Drought Mitigation Center, 2014; Zargar et al., 2011).

Of key importance for land managers planning for drought events of any time scale is characterising the return period or frequency of occurrence of rainfall and drought events. The recurrence interval is defined as the average inter-occurrence time of any geophysical phenomena and is calculated with long-term time series data (Loaiciga and Mariño, 1991). Recurrence intervals of rainfall events greater than the average are commonly used by engineers to derive intensity-duration-frequency (IDF) design estimates for building hydraulic infrastructure such as roofs, culverts, stormwater drains, bridges or water dams (Chebbi et al., 2013; Kuo et al., 2013; Hailegeorgis et al., 2013). IDF design rainfalls are crucial for estimating the risk of hydraulic infrastructure failure and for maximising infrastructure efficiencies (Smithers et al., 2002). Similar to the concept of IDF design rainfall, which aims to quantify the recurrence interval if rainfall events based on their intensity and duration, we apply the same concept to quantify the recurrence intervals of droughts based on their severity and duration, and refer to this concept as severity-duration-frequency (SDF) design drought. SDF curves have been used to derive drought variables in different climatic regions (Shiau, 2006; Shiau et al., 2012) but have rarely been used in ecology, and never been used in relation to rehabilitation and restoration. While IDF design rainfalls are a well-established tool in civil engineering and hydrology, we believe SDF design drought could be used in a similar way to assess the risk of ecosystem rehabilitation failure due to droughts.

This approach contrasts current climate classifications methods (Table 1) that are used for the management of agricultural land (e.g. classification of Australian agricultural environments or Australian agro-climatic classes) (Hutchinson et al., 2005; Woodhams et al., 2012; Audet et al., 2013). These classifications are based on average climatic conditions and may not be adequate for the management of early re-establishment of vegetation in post-mining landscapes (Audet et al., 2013; Audet et al., 2012) because of the vulnerability of vegetation to drought events. Although droughts play a critical role in post-mining land restoration in Eastern Australia, so far methods for quantifying the frequency of drought events have been rarely applied to assess the risk of failure of ecosystem rehabilitation in post mined lands due to droughts. In the perspective of mined land rehabilitation, specific metrics of site climate or seasonality are surprisingly rare (Audet et al., 2013).

The objective of our study is to quantify the severity, duration, and frequency (SDF) of short-term and long-term drought events at selected locations across a broad range of agro-climatic environments in Eastern Australia (Table 1, Fig. 1). While other studies assessed the SDF characteristics at locations with the same climate in Iran (Shiau and Modarres, 2009; Shiau et al., 2012), no such investigations are known for any climatic region in Australia, neither for the same climate nor across different climates.

We characterised droughts using the RDI and SPEI for 3 and 12-month time scales respectively, and compared these indices with the SPI at the same time scales. We then linked the univariate distributions of severity and duration calculated with the drought indices to form bivariate distribution functions and estimated the recurrence intervals of droughts. Note, since the estimated recurrence intervals are based on historic rainfall and evaporation data, our results are descriptive rather than predictive. Nevertheless, our findings are crucial to discuss the potential of design droughts to be applied as a management tool to overcome the challenges of early vegetation establishment and long-term ecosystem resilience in post-mining landscapes, because frequency patterns of drought events are ignored in any current rehabilitation guidelines and industry plans, where long-term average rainfall is the only parameter upon management decisions are based on (Audet et al., 2013).

2 Materials and methods

Estimating SDF curves involves uncertainties associated with the length of the observed rainfall data, the applied drought index, the probability distribution functions used to fit the observed severity and duration, and the estimated copula parameter (Hu et al., 2014). To overcome these uncertainties we tested the applicability of drought indices for locations in different climatic regions by calculating the correlation of three selected drought indices. Likewise we used the best fitted probability distribution functions and copula for each site. A flow chart of the processing steps is depicted in a schematic diagram (Fig. 2).

We selected 11 sites for which historical observations of monthly rainfall and evaporation (Table 1) were most comprehensive (i.e., longest and most complete) across Eastern

Australia (Bureau of Meteorology, 2013). The selected locations covered a broad range of climate classes and environments across Eastern Australia (Table 1, Fig. 1).

For each site we compared the simple SPI with the more complex RDI and SPEI drought indices. Amongst the three indices the SPI is the most widely used and simplest drought index, because it is solely based on long-term rainfall for any period of interest (McKee et al., 1993; Guttman, 1999). However, SPI may not adequately characterise drought events due to the lack of other meteorological data (Vicente-Serrano et al., 2010; Mishra and Singh, 2010). Both the RDI and SPEI integrate potential evaporation and thereby better represent the local water balance (Tsakiris, 2004; Tsakiris and Vangelis, 2005; Tsakiris et al., 2007; Vangelis et al., 2013).

The drought indices can be calculated using monthly values of rainfall and/or potential evaporation. Amongst the two indices which incorporate potential evaporation, the RDI represent short and medium time-scale (3 to 6 months) drought events very well (Banimahd and Khalili, 2013), while the SPEI plays a strong role in detecting annual drought events (Egidijus et al., 2013). For short time scales, we compared SPI_3 with RDI_3 (3 months) and at long time scales we compared SPI_{12} with $SPEI_{12}$ (12 months) for each location.

2.1 Step 1: Calculate drought indices

The SPI is derived by fitting a probability distribution to the rainfall record and then transforming that to a normal distribution such that mean and standard deviation of the SPI are zero and one. Positive or negative values of the SPI represent rainfall conditions greater or smaller than average rainfall, respectively (Edwards, 1997). RDI and SPEI are based on the SPI calculation procedure, except the two indices use the quotient or difference of precipitation and potential evaporation, respectively (Tsakiris et al., 2007; Vicente-Serrano et al., 2010). Equations for the RDI and SPEI are presented in Appendix A. We applied two correlation coefficients to assess the correlations between SPI_3 and RDI_3, and SPI_{12} with $SPEI_{12}$ (step 1 in Fig. 2): Kendall's tau to assess the number of concordances and discordances in paired variables (RDI_3 and SPI_3, $SPEI_{12}$ and SPI_{12}), and Pearson's r to measure linear correlation.

2.2 Step 2: Bivariate distribution of drought severity and duration

For each location, we used the estimated drought indices (SPI, RDI, SPEI), hereafter collectively referred to as *I*, to quantify duration *D* and severity *S* (McKee et al., 1993;

Vicente-Serrano et al., 2010; Tsakiris and Vangelis, 2005). The duration of any drought was defined as the period of rainfall deficit, i.e. the cumulative time of negative *I* values preceded and followed by positive *I* values (Fig. 3). The severity of any drought period starting at the i^{th} month was defined as:

$$S = \sum_{i=1}^{D} |-I_i| \tag{1}$$

We fitted the time series of *D* and *S* to a range of cumulative distribution functions (gamma, logistic, extreme value, lognormal, bimodal lognormal, and bimodal logistic) and used the function with the best fit for further investigations (step 2 in Fig. 2). The coefficient of determination and 95% significance levels were calculated for each distribution in order to select the best distribution.

2.3 Step 3: Estimate copula parameter

We used copulas to link the univariate probability distributions of *D* and *S* to construct a bivariate joint distribution of *D* and *S* (Shiau and Modarres, 2009; Sklar, 1959) (step 3 in Fig. 2). As the choice of copula can be very different from one climate region to another (Khedun et al., 2013) the present study focused on the Frank and Gumbel copula (Appendix B), as they have been shown to perform best when analysing the bivariate drought dependence structure of drought variables such as severity and duration (Ganguli and Reddy, 2012; Reddy and Ganguli, 2012; Shiau, 2006; Lee et al., 2013; Wong et al., 2010; Zhang et al., 2011). Copulas have been applied across a range of disciplines such as hydrology (Zhang et al., 2011; Shiau and Shen, 2001; Shiau et al., 2007; Li et al., 2013), engineering (Lebrun and Dutfoy, 2009), meteorology (Liu et al., 2011; Madadgar and Moradkhani, 2011), and economics (Wang et al., 2013; Dajcman, 2013). The conditional cumulative distribution function $F_{S|D}(s|d)$ relates to the joint cumulative distribution function (JCDF) of drought severity and duration $F_{S,D}(s,d)$ and the cumulative distribution function (CDF) of drought duration $F_D(d)$ is given by the following relationship (Shiau and Modarres, 2009):

$$F_{S|D}(s|d) = \frac{\partial F_{S,D}(s,d)}{\partial\, F_{D\,(d)}}, \tag{2}$$

where $F_D(d)$ is the CDF of drought duration, and $F_{S,D}(s,d)$ is the JCDF of drought severity and drought duration. The JCDF of drought severity and duration in terms of copulas is a function of univariate CDFs of duration and severity:

$$F_{S,D}\ (s,d) = C(F_S(s), F_D(d)), \tag{3}$$

where $F_s(s)$ and $F_D(d)$ are CDFs for drought severity and duration, respectively, and C is a copula function. The conditional distribution function $F_{S|D}$ (s|d) (Eq. 2) can also be expressed as a function of the copula (Shiau and Modarres, 2009):

$$F_{S|D}\ (s|d) = \frac{\partial F_{S,D}(s,d)}{\partial F_D(d)} = \frac{\partial C(F_S(s),\ F_D(d))}{\partial F_D(d)} = C_{F_S|F_D}\left(F_S(s)\middle|F_D(d)\right), \tag{4}$$

We estimated the copula parameters using the Inference Function for Margins (IFM) (Joe, 1997). The IFM comprises two separate valuation stages. First, the maximum likelihood estimation of each univariate distribution is performed, and then the copula dependence parameter is estimated to derive the joint drought duration and severity distributions (Shiau, 2006; Shiau and Modarres, 2009; Mirabbasi et al., 2012; Shiau et al., 2007).

2.4 Step 4: Derive recurrence intervals

We used the estimated copula parameters to generate random drought events. Severity and duration of the generated random droughts were then fitted to cumulative distribution functions in the same manner as in step 2 (Fig. 2, step 3) to test which estimated copula parameters result in a distribution that best fit the generated random drought variables. The estimated copula parameters were also assessed quantitatively through calculating the correlation between generated random drought events and the estimated gamma (*S*) and logistic (*D*) cumulative distribution functions.

The generated random numbers were then used to calculate the recurrence intervals. Recurrence intervals of bivariate drought events is a standard metric for hydrological frequency analysis (Yoo et al., 2013; Hailegeorgis et al., 2013) and water resources management (Shiau and Modarres, 2009; Mishra and Singh, 2010). For each location, we calculated the recurrence interval of drought events exceeding any severity *or* duration of interest, denoted by the logical operator “∨”:

$$T_I^{\vee} = \frac{1}{P(S \geq s \vee D \geq d)} = \frac{1}{1 - C[F_S(s), F_D(d)]}. \tag{5a}$$

where *I* is one of the drought indices of interest, i.e., the 12-monthly $SPEI_{12}$ or SPI_{12}, or the three-monthly RDI_3 or SPI_3. Alternatively, the recurrence interval of drought events exceeding any severity *and* duration of interest, denoted by the logical operator “∧”, was calculated as:

$$T_I^{\wedge} = \frac{1}{P(S \geq s \wedge D \geq d)} = \frac{1}{1 - F_S(s) - F_D(d) + C[F_S(s), F_D(d)]}, \qquad (5b)$$

For the sake of simplicity, we only present and discuss $T_I^{\vee}$, whereas $T_I^{\wedge}$ is presented in Appendix D.

3 Results

For both indices and all selected sites, RDI and SPEI, the gamma and logistic distributions fitted best to the observed drought severity and duration, respectively ($R^2 > 0.98$ for both variables, $p < 0.05$). Likewise, the same distributions fitted best to the drought severity and duration of the generated drought events based on the Frank rather than the Gumbel copula ($R^2 > 0.90$, $p < 0.05$).

Based on the drought indices RDI_3 and $SPEI_{12}$ we detected distinct drought patterns across the selected sites at short and long-term scales, respectively. As an example of differences between tropical, temperate and arid rainfall conditions, Figure 4 depicts calculated time series of RDI_3 and $SPEI_{12}$ for Weipa, Sydney and Quilpie, respectively. For each location RDI_3 detected more drought events (i.e., $RDI_3 < 0$) of short duration and lower severity than $SPEI_{12}$ (Table 2).

Short-term droughts were most severe and prolonged in tropical Weipa and Cairns, and temperate Wagga Wagga (Table 2). However, in contrast to Wagga Wagga, the two tropical locations were characterised by distinct seasonality patterns and very low variation as indicated by the low ratio of winter to summer rainfalls (Table 1) and low coefficients of variation in severity and duration (Table 2). The highest variation in severity was detected in arid Bourke and temperate Brisbane (Table 1).

Long-term droughts were most severe and prolonged in arid Quilpie (Table 2) and rare in temperate Melbourne. Likewise, severity and duration varied most at the two locations, together with arid Bourke. While severity and duration were moderately high in arid Mount Isa and temperate Brisbane, both parameters were low across the other selected temperate and tropical locations (Table 2).

No significant differences were detected (P >0.05 at 95% confidence level) between RDI_3 and SPI_3, and $SPEI_{12}$ and SPI_{12} (Fig. 5 and Appendix E). Correlation between RDI/SPEI and

SPI was greatest for tropical Cairns and Weipa, and lowest for arid Bourke and Quilpie (outliers in Fig. 5). Interestingly, although Mount Isa was being the most arid location (R/PET = 0.13, Table 1) the correlations between drought indices was relatively strong with values of 0.903 (Pearson's r) and 0.759 (Kendalls'tau) for long-term droughts.

For each location, the recurrence intervals of drought events exceeding any severity *or* duration of interest are depicted in figure 6 for short-term droughts (based on RDI_3) and Figure 7 for long-term droughts (based on $SPEI_{12}$). Short-term droughts recurred most frequently in arid Mount Isa and were relatively rare in tropical Weipa and Cairns, and temperate Sydney. For example, in Mount Isa a drought with severity of 14 or duration of 17 months[1] recurred once in 50 years, whereas the same drought recurred only once in 100 000 years in Weipa, 300 years in Cairns, and 100 years in Sydney (Fig. 6). Long-term droughts recurred most frequently in arid Quilpie, where droughts with severity of 18 or duration of 10 months recurred once in 2 years. In Kingaroy and Sydney the same design drought recurred only once in 4 and 5 years, respectively (Fig. 7). Interestingly, although average long-term droughts were very severe and prolonged in Melbourne (Table 2), they only recurred once in 30 to 50 years. We found the same qualitative patterns in all locations for recurrence intervals of droughts exceeding any severity *and* duration of interest (Appendix D).

4. Discussion

In this study we estimated the recurrence intervals of short- and long-term droughts based on meteorological drought indices and copulas (i.e., bivariate probability distributions). For both time scales the correlation between the simple SPI (rainfall) and the more complex SPEI or RDI (rainfall and evaporation) was much stronger for the tropical and temperate locations (e.g., Cairns, Weipa, Brigalow) than for the arid locations (e.g., Quilpie, Bourke, Wagga Wagga). Extending a former study on abiotic boundaries affecting ecological development of post-mining landscapes (Audet et al., 2013), our findings have critical implications for assessments of rehabilitation success.

The short-term drought index (RDI_3) detects most severe and prolonged droughts in tropical Weipa and Cairns (Table 2), where rainfall is low in winter and high in summer. Annually

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[1] Drought events are calculated by 3 (short-term) and 12 (long-term) month running precipitation totals (Guttman, 1999).

recurring seasonal patterns also explain the low variability of short-term drought severity and duration. In contrast the long-term drought index ($SPEI_{12}$) detects most severe and prolonged droughts in arid Quilpie and Mount Isa, as well as temperate Melbourne (Table 2). Major weather events such as El Niño and La Niña from recent decades coincided with low and high drought indices, respectively (Fig. 4 and Appendix C). However, due to smaller index fluctuations these major events are more pronounced in the context of long-term droughts ($SPEI_{12}$) (Fig. 4, and Appendix C).

4.1 Implications for ecosystem rehabilitation planning

Across Eastern Australia current post-mining land rehabilitation strategies often do not incorporate site-specific rainfall and drought metrics other than the average annual rainfall depth (Audet et al., 2013). However, regionally extreme rainfall patterns, including both intense rainfall events such as storms or cyclones and prolonged periods of water deficit (droughts), play a critical role in identifying windows of opportunity and/or challenge to the rehabilitation of early-establishment ecosystems (Hinz et al., 2006; Hodgkinson et al., 2010). Furthermore, Audet et al. (2013) suggested that short and long-term ecosystem rehabilitation sensitivity to climate can be effectively determined by the seasonality, regularity, and intensity of weather, combined with both median and standard deviation of periods. In particular prolonged seasonal drought with high variation and frequently occurring intense rainfall can be used as a primary characteristic for determining site sensitivity while regular rainfall and relatively short periods of water deficit are common characteristics of favourable climate conditions. Based on their findings, Audet et al. (2013) revealed how broad scale rainfall patterns outline climate boundaries that drive rehabilitation sensitivity in arid to temperate locations across Eastern Australia. For example, ecosystem rehabilitation in arid regions (Mount Isa, Quilpie, and Bourke) is sensitive to climate as they have heavily variable climates (long spell of droughts and high intensity rainfall), which affect the success of rehabilitation.

Commonly the characterisation of climatic conditions is based on long-term rainfall and do not consider short and long-term drought conditions. Identifying drought and its variables are critical factors in ecosystem rehabilitation because the distribution and health of plant species are vulnerable to droughts and plant available water (Engelbrecht et al., 2007). In our study we presented two hydrological parameters describing the average recurrence intervals of short-term and long-term droughts (Figs. 6, 7 and Appendix D), which can be used instead of the oversimplified parameters of median period without rain and standard deviation normally used (Audet et al., 2013).

The design drought tool proposed in this paper is an adaptation of the intensity-duration-frequency (IDF) analysis of rainfall events, a standard tool used by engineers (Hailegeorgis et al., 2013; Chebbi et al., 2013). Our new term “design droughts”, characterised by drought severity-duration-frequency (SDF), is based on the severity of droughts (negative values of Fig. 3) as opposed to IDF which is based on the intensity of the rainfall. Design droughts allow for drought severity, duration and frequency to be considered in order to determine the risk of failure of current mining operations (Mason et al., 2013; Burton et al., 2012), and to design robust ecosystem components in the face of the local climate variability (Audet et al., 2013). Unlike degraded land (in the sense of gradual loss of ecosystem productivity), in post-mining landscapes most ecosystem components are impacted by mining activities, particularly landform, hydrology, and ecosystem structure (Arnold et al., 2014b). Therefore, successful rehabilitation of post-mining land requires the sensible selection of plant species, as well as planting/seeding regime, soil characteristics, irrigation method, and landform characteristics (Table 3). For example, certain vegetation types will not establish if there is a drought greater than a specific duration or severity (Arnold et al., 2014a). The recurrence intervals can provide the probability of a drought occurring at this duration or severity, and thus the risk of establishment failure can be assessed. This is important for rehabilitation managers who can conduct a cost-benefit analysis to decide whether costs of constructing mitigation methods such as irrigation are comparable with the costs of potential failure of multiple revegetation attempts.

Together, design rainfalls (IDF) and droughts (SDF) should be the primary determinants of rehabilitation strategies and eventually help to guide rehabilitation planning, where environmental conditions have an impact on current mining operations. In accordance with IDF parameters of similar locations across Eastern Australia (Audet et al., 2013), temperate and tropical environmental conditions (Table 1) are favourable for ecological development, i.e. recurrence intervals of droughts are large (Figs. 6, 7 and Appendix D). By contrast, re-establishment of ecosystems is prone to failure in arid conditions, where droughts recur more frequently (i.e., low recurrence intervals). However, locations with distinct patterns of seasonality such as Weipa, Cairns, or the Brigalow Belt are the exception to this pattern due to the distinct distribution of winter and summer rainfalls (Table 1).

We compared SPI with SPEI or RDI to determine the potential of using SPI (only based rainfall data) over SPEI or RDI (both based on rainfall and evaporation data). This might be of interest for many parts of the world, where evaporation data are unavailable or incomplete and therefore simple rainfall indices are most commonly used. Our analysis revealed that Pearsons'r and Kendall's tau correlations were strong across the selected locations (Fig. 5 and Appendix E), indicating the potential of the simple SPI to serve as a surrogate for the more complex RDI and SPEI. For temperate and tropical environments such as Cairns, Weipa, or Brisbane the more complex RDI and SPEI can be replaced by the simple SPI if evaporation data is not available (Fig. 5 and Appendix E). By contrast, in arid Bourke, Quilpie, or Mount Isa correlations between SPI and the more complex indices were weaker. In these arid and water-limited locations (Table 1) we recommend using SPEI and RDI[2] and also to conduct intensive monitoring of ecosystem development in relation to empirical weather data to measure evaporation directly, e.g. pan evaporation (Lugato et al., 2013; Clark, 2013), or indirectly, e.g. based on radiative and aerodynamic variables (Allen et al., 1998).

4.2 SDF curves as an early risk assessment tool

Risk assessment based on the design rainfall concept is commonly used as a standard tool by engineers to design infrastructure such as storm water drains, flood mitigation levees, or retarding dams (Chebbi et al., 2013; Hailegeorgis et al., 2013). This research paper aims to demonstrate how these concepts can be used for ecosystem rehabilitation, providing a quantitative estimate of ecosystem rehabilitation failure due to water deficit. Traditionally, ecologist and land managers often use the mean annual rainfall as a co-classifier of biogeographic regionalisation. However, annual rainfall alone cannot account for the vulnerability of a site to non-disruptive water supply, the frequency of water limitations, and seasonality (Audet et al., 2013). For example, although mean annual rainfall is lowest in Bourke, the SDF analysis reveals that severe and prolonged droughts occur most frequently in Mount Isa. This is because in Mount Isa on average 23 out of 100 days are with no rainfall as most of the rainfall occurs in summer as storm events greater than 100 mm (Table 1) (Bureau of Meteorology, 2013). Ecosystem rehabilitation may fail if management actions are

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[2] Note that the definition and quantification of drought are normative. In this regard, our results indicate under what climatic conditions SPEI and RDI can be replaced by SPI rather than which index is the best one for each location.

based only on the annual rainfall without considering the nature of drought events (i.e., the rate of recurrence of prolonged and severe droughts) (Table 3).

Quantitatively, risk is the product of the probability of an event occurring and the consequences of an event on assets (Athearn, 1971). In the context of post-mining land rehabilitation, the recurrence intervals quantify the probability of occurrence of drought events. If the consequences of drought events for ecosystems are known (Wilhite et al., 2007; Williamson et al., 2000) the risk of ecosystem rehabilitation failure can be quantified. Consequences will typically have to be determined in relation to site specific attributes such as plant species, soil, irrigation etc. (Table 3). Likewise, the consequences can also be related to the costs of rehabilitation. For example, for frequently recurring droughts of high severity and duration irrigation may be a cost-efficient alternative to repeatedly replanting at a rehabilitation site due to establishment failure. These consequences in relation to severity and duration may be identified from the literature, field trials or be derived from expert opinion. A key aspect of our study is that SDF curves provide the probability of occurrence of drought events with a specific duration and severity.

4.3 Application of design droughts to rehabilitation planning

One of the major outcomes of this study is to support land managers and/or rehabilitation practitioners to make fundamental decisions on appropriate management actions in the context of drought frequency. For rehabilitation to be successful in the face of severe and prolonged droughts, there are a range of management domains and management actions that need to be considered in response to recurrence intervals, drought severity, and drought duration (Table 3). These management actions can be categorised into four domains: plant species selection, planting/seeding regime, soil characteristics, and irrigation method.

Meteorological droughts indicate deviations of rainfall and/or evaporation relative to the long-term average. Native climax vegetation, which is well adapted to the local climate, is hardly sensitive to these anomalies. However, within the process of post-mining land rehabilitation, establishment of well-adapted climax vegetation is impossible. In fact, post-mining ecosystem rehabilitation is very sensitive to decisions made on the re-established topography and soil characteristics, as well as planting/seeding regimes and irrigation methods (Table 3). In this regard, the frequency of meteorological droughts relative to long-term conditions is the critical driver of these management decisions. For example, seedling establishment might fail under conditions of frequently occurring short-term droughts even if the absolute rainfall in between droughts is high. Under these conditions, landform and soil need to be restored such that periods of water limitation can be minimised.

Selection of suitable plant species based on drought type is one of the key management actions for successful rehabilitation. Some management actions can be applied to all drought types (LS, LP, SS, SP in Table 3). These include (i) planting of drought tolerant species (e.g., *Acacia* spp., *Banksia* spp., *Casuarina* spp.), at (ii) northern aspects to address drier conditions that result from higher solar radiation causing increased evaporation (Sternberg and Shoshany, 2001), and (iii) planting of perennial grasses (*Eragrostis* spp., *Themeda* spp. (Bolger et al., 2005)), which may not be affected by long-term water deficits. At locations with frequently recurring long-term (12 month time scale) droughts of high severity and durations (LS, LP in Table 3), such as Mount Isa and Quilpie, seeding of species with physical/chemical dormancy may increase the probability of germination during favourable periods (Hilhorst, 1995; Arnold et al., 2014b). Additionally, a southern aspect may require drought tolerant species to increase survival of plant communities (Sternberg and Shoshany, 2001). However, these species need to be shade tolerant as southern aspects get less solar radiation in winter. At locations with frequently recurring short-term (3 month time scale) droughts of high severity but short duration, with rainfall throughout the year (SS in Table 3), such as Wagga Wagga, annual grasses and seeds with short germination periods may be suitable.

Soil characteristics play a critical role for plant available water and a number of strategies may need to be employed to make soil more favourable to plant establishment. Except for mulching, all of the management actions within the soil characteristics management domain can be applied to locations with high recurrence of long-term, severe, and prolonged droughts (LS, LP in Table 3), such as Quilpie and Mount Isa. For locations with high recurrence of short-term, and prolonged droughts (SP in Table 3), such as Melbourne, increasing the depth of topsoil can increase water holding capacity (Audet et al., 2013; Bot and Benites, 2005). Similarly, by mixing silt and clay soil in the topsoil and reducing slope gradients may facilitate infiltration and increase soil water retention capacity (Audet et al., 2013). For tropical locations with high recurrence of short-term (3 month time scale), severe, and prolonged droughts (SS, SP in Table 3), such as Cairns and Weipa, ground cover such as mulch and planting fast growing cover (e.g., Buffel grass) may reduce evaporation and maintain soil moisture to allow for the establishment of drought sensitive and slow growing species (Blum, 1996).

Utilising irrigation methods for specific site characteristics is a cost effective strategy for any rehabilitation plan. Regular irrigation with proper drainage systems that distributes water is an effective strategy in locations with high recurrence of long-term, severe, and prolonged droughts (LP, LS in Table 3). For locations with high recurrence of short-term, severe, and prolonged droughts (SS, SP in Table 3), with seasonal rainfall (e.g. Brisbane, Sydney, Kingaroy, Brigalow), seasonal irrigation and irrigation at critical stages of plant growth (Blum, 1996), such as germination, and root or pod development periods are efficient actions to ensure plant survival throughout drought spells.

4.4 Future research

The method outlined in this study provides a useful tool for land managers to address site-based climatic conditions. Future research needs to build on this tool, as well as address the limitations of our method based on meteorological drought indices inferred from point observations. This research may assess: (i) the relationship between meteorological and agricultural drought indices, (ii) regional scale mapping of drought indices and, (iii) the predictive power of design droughts.

While the applied drought indices are robust indicators of meteorological droughts (Mishra and Singh, 2010; Quiring, 2009), they are limited to detecting anomalies from historic rainfall patterns. Soil plays a critical role for any ecosystem development, particularly with regard to ecosystem rehabilitation in post-mining land (Arnold et al., 2013), as soil properties translate rainfall into plant available water (Zhang et al., 2001; Huang et al., 2013). Future drought analysis would benefit from integrating soil properties such as depth, texture, salinity, or organic matter content into drought indices to describe agricultural droughts (Khare et al., 2013; Baldocchi et al., 2004; Woli et al., 2012). Soil texture and depth are critical factors in highly seasonal climates, where the soil forms the water storage to overcome periods of water deficit (Prentice et al., 1992; Bot and Benites, 2005). However, using simple and easily accessible meteorological data is a critical step forward to making it easier for mine rehabilitation managers to adopt the concept of using SDF curves as early risk assessment tool.

Although the selected locations can be considered representative of the agro-climatic environments across Eastern Australia (Fig. 1), our analysis is strictly valid for the selected point data and therefore site-specific. Future work should not only integrate the above mentioned soil component but also extend drought analyses across Australia using gridded weather data from the Bureau of Meteorology (2014). Future investigations could assess possible trends in temporal changes of recurrence intervals by dividing historic time series of rainfall and evaporation into subsets and replicate the analysis for each subset (Li et al., 2014; Darshana et al., 2013; Jacobs et al., 2013).

5 Conclusions

The study revealed site-specific patterns of recurrence intervals of short-term and long-term droughts across Eastern Australia. Severe and prolonged short-term droughts recurred most often in tropical climates and temperate Wagga Wagga, while severe and prolonged short-term droughts recurred most often in arid conditions and temperate Melbourne. Design droughts can be applied to quantify the frequency of drought events – characterised by severity and duration – at different time scales. This is a critical step forward to consider drought in risk assessments for rehabilitation of post-mining ecosystems. Together with design rainfalls, design droughts should be used to assess rehabilitation strategies and ecological management based on drought recurrence intervals, thereby minimising the risk of failure of initial ecosystem establishment due to ignorance of fundamental abiotic and site-specific environmental barriers.

Appendix A. RDI and SPEI

A1 RDI

where

The standardised RDI_{st} is given as:

$$RDI_{st}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k}, \qquad \text{(A1)}$$

with

$$y_k = ln \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \qquad \text{(A2)}$$

where $\hat{\sigma}$ is the standard deviation, y_k is month k of year y, $\bar{y}_k$ is the arithmetic mean of y_k, $\hat{\sigma}_k$ is the standard deviation of y_k, and P_j and PET_j are precipitation and potential evapotranspiration for the j^{th} month of the hydrological year, respectively (Tsakiris and Vangelis, 2005).

A2 SPEI

The SPEI is calculated as:

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3}, \qquad \text{(A3)}$$

with

$$W = \sqrt{-2\,ln(P)} \quad for\ P \leq 0.5, \qquad \text{(A4)}$$

Where *P* is the probability of exceeding a determined value of the difference between the precipitation and potential evapotranspiration (*P* = 1- F(x)). If *P* > 0.5, then *P* is replaced by 1 - *P* and the sign of the resultant SPEI is reversed. The constants are C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328, d_1=1.432788, d_2=0.189269, and d_3=0.001308 (Vicente-Serrano et al., 2010).

Appendix B. Mathematical description of Gumbel and Frank copula (Shiau, 2006).

B1 Gumbel copula

$$C(u,v) = exp\left\{- \left[(-ln\, u)^{\theta} + \left(-\, ln\, v\right)^{\theta}\right]^{\frac{1}{\theta}}\right\} \; \theta \geq 1 \qquad \text{(B1)}$$

$$\mathrm{c}(u,v) = C\,(u,v)\frac{\left[\,(-1ln\, u)^{\theta}\,(-\, ln\, v)^{\theta-1}\right]}{uv} \;\; \left[\,(-1ln\, u)^{\theta}\,(-\, ln\, v)^{\theta}\right]^{\frac{2}{\theta}-2} \qquad \text{(B2)}$$

$$.\left\{(\theta-1)\left[(-ln\, u)^{\theta} + \left(-\, ln\, v\right)^{\theta}\right]^{-\frac{1}{\theta}} + 1\right\}$$

B2 Frank copula

$$C\,(u,v) = -\frac{1}{\theta}ln\left[1 + \frac{\left(e^{-\theta u}-1\right)\left(e^{-\theta v}-1\right)}{e^{-\theta}-1}\right], \theta \neq 0 \qquad \text{(B3)}$$

$$c(u,v) = -\frac{\theta e^{-\theta(u+v)}\;\left(e^{-\theta}-1\right)}{[e^{-\theta(u+v)} - e^{-\theta u} - e^{-\theta v} + e^{-\theta}]^{2}} \qquad \text{(B4)}$$

Appendix C. Time series of drought indices and major weather events.

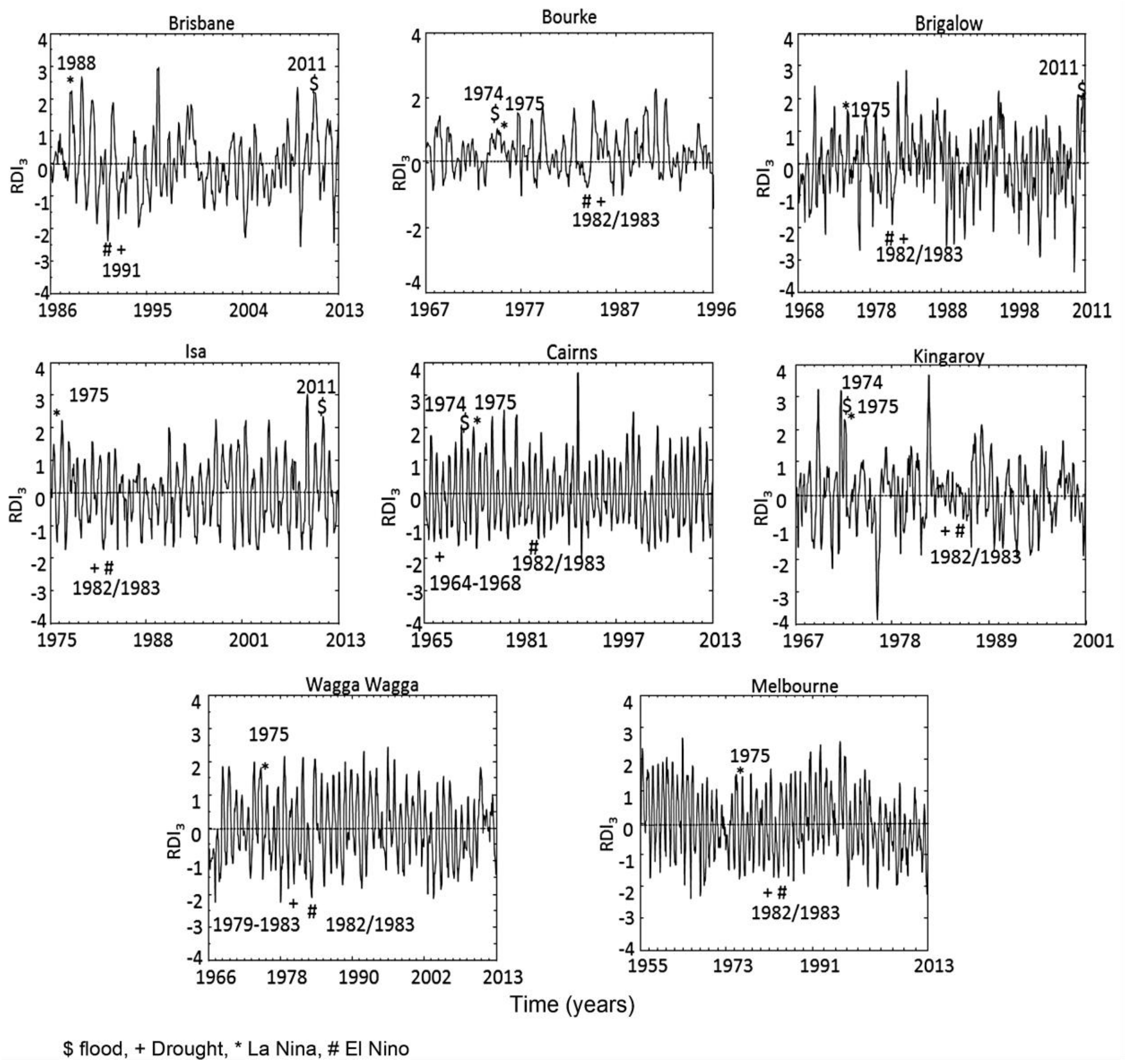

Figure C1. Calculated $SPEI_{12}$ for selected locations across Eastern Australia.

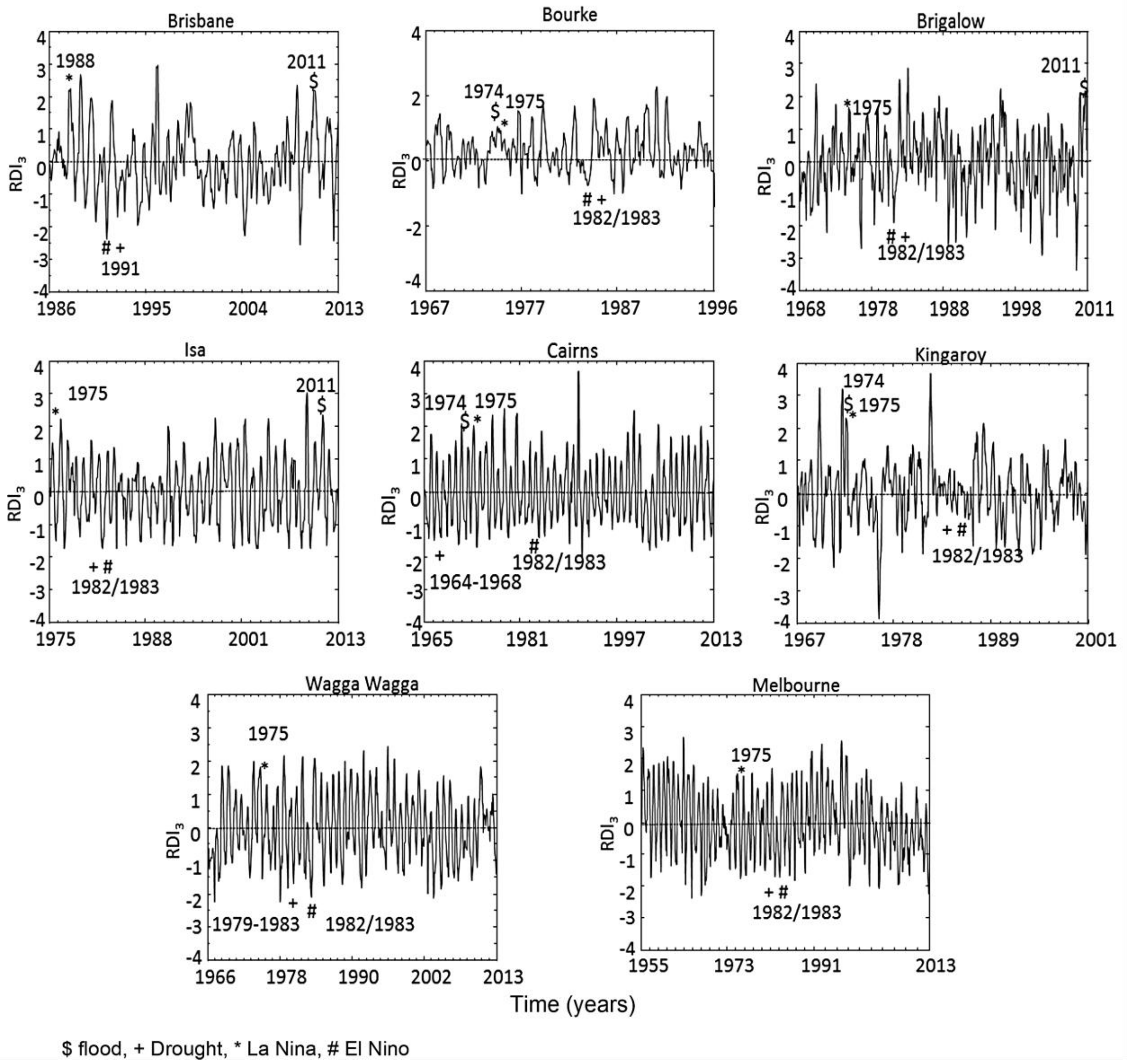

Figure C2. Calculated RDI$_3$ for selected locations across Eastern Australia.

Appendix D. Recurrence intervals of drought events with any severity *and* duration of interest.

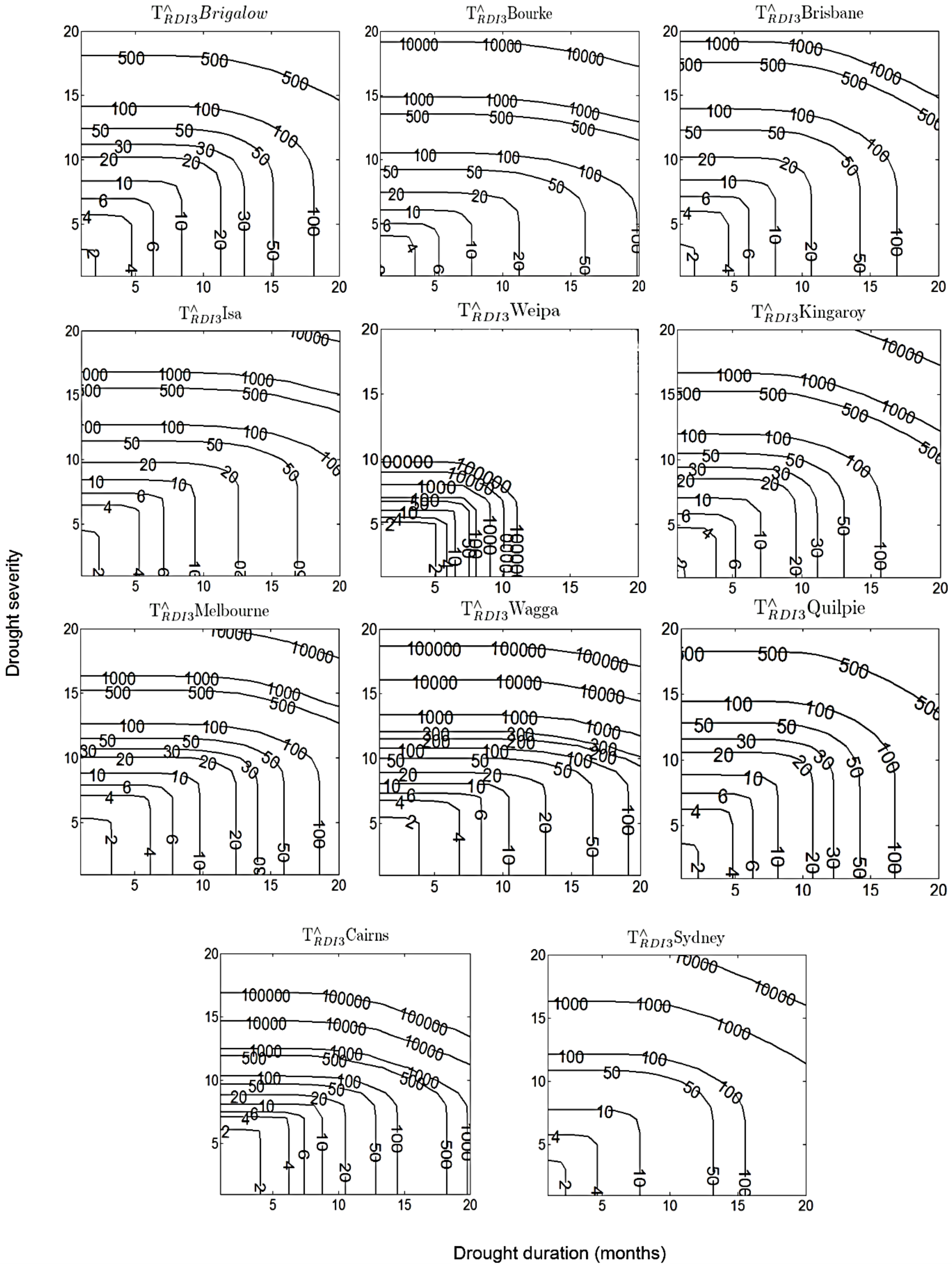

Figure D1. Recurrence intervals T^ (years) of drought events with any severity *and* duration of interest based on RDI$_3$ (short-term) of historical rainfall.

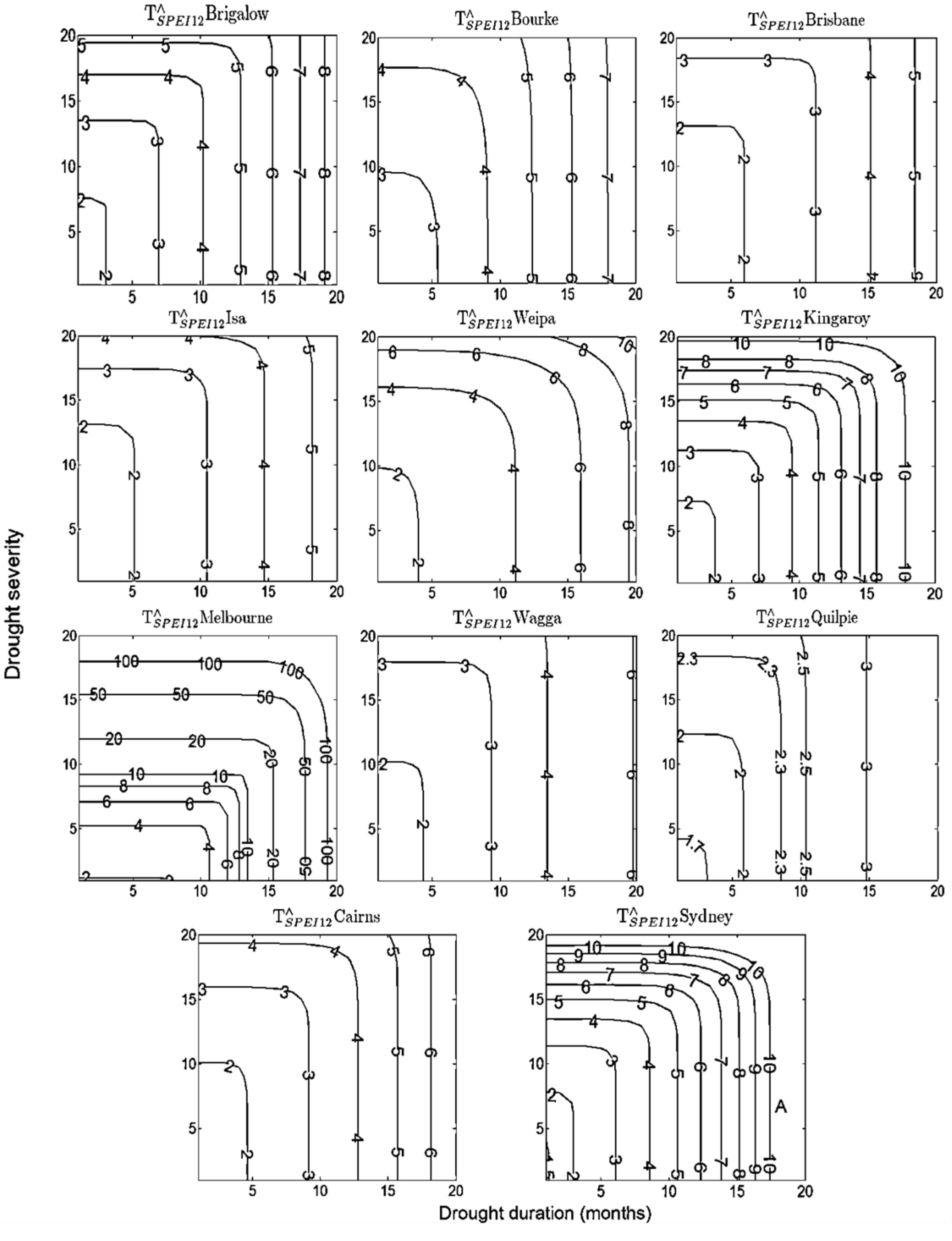

Figure D2. Recurrence intervals T^ (years) of drought events with any severity *and* duration of interest based on $SPEI_{12}$ (long-term) of historical rainfall.

Appendix E. Coefficient values of Pearson’s r and Kendall tau for SPI_3 vs. RDI_3, and SPI_{12} vs. $SPEI_{12}$.

Table E. Coefficient values of Pearson’s r and Kendall tau for SPI_3 vs. RDI_3, and SPI_{12} vs. $SPEI_{12}$. Correlations were lowest for arid Bourke and Quilpie (bold values).

Location	SPI_3 vs. RDI_3		SPI_{12} vs. $SPEI_{12}$	
	Pearson’s r	Kendall tau	Pearson’s r	Kendall tau
Weipa	0.98	0.92	0.83	0.68
Cairns	0.98	0.90	0.96	0.83
Brisbane	0.81	0.62	0.68	0.68
Sydney	0.82	0.61	0.90	0.71
Melbourne	0.98	0.90	0.82	0.70
Kingaroy	0.77	0.54	0.87	0.68
Brigalow	0.90	0.71	0.83	0.64
Wagga Wagga	0.69	0.68	0.84	0.71
Bourke	**0.43**	**0.54**	**0.51**	**0.53**
Quilpie	**0.57**	**0.40**	**0.49**	**0.40**
Mount Isa	0.78	0.60	0.72	0.67

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References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO, Rome, Italy, 300 pp., 1998.

Anderegg, L. D., Anderegg, W. R., and Berry, J. A.: Not all droughts are created equal: translating meteorological drought into woody plant mortality, Tree physiology, 33, 672-683, 2013.

Arnold, S., Audet, P., Doley, D., and Baumgartl, T.: Hydropedology and Ecohydrology of the Brigalow Belt, Australia: Opportunities for Ecosystem Rehabilitation in Semiarid Environments, gsvadzone, 0, -, 10.2136/vzj2013.03.0052, 2013.

Arnold, S., Kailichova, Y., and Baumgartl, T.: Germination of Acacia harpophylla (Brigalow) seeds in relation to soil water potential: implications for rehabilitation of a threatened ecosystem, PeerJ, 2, e268, 10.7717/peerj.268, 2014a.

Arnold, S., Kailichova, Y., Knauer, J., Ruthsatz, A. D., and Baumgartl, T.: Effects of soil water potential on germination of co-dominant Brigalow species: Implications for rehabilitation of water-limited ecosystems in the Brigalow Belt bioregion, Ecological Engineering, 70, 35-42, http://dx.doi.org/10.1016/j.ecoleng.2014.04.015, 2014b.

Athearn, J. L.: What is Risk?, The Journal of Risk and Insurance, 38, 639-645, 10.2307/251578, 1971.

Audet, P., Arnold, S., Lechner, A., Mulligan, D., and Baumgartl, T.: Climate suitability estimates offer insight into fundamental revegetation challenges among post-mining rehabilitated landscapes in eastern Australia, Biogeosciences Discussions, 9, 18545-18569, 2012.

Audet, P., Arnold, S., Lechner, A., and Baumgartl, T.: Site-specific climate analysis elucidates revegetation challenges for post-mining landscapes in eastern Australia, Biogeosciences, 10, 6545-6557, 2013.

Baldocchi, D. D., Xu, L., and Kiang, N.: How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak–grass savanna and an annual grassland, Agricultural and Forest Meteorology, 123, 13-39, http://dx.doi.org/10.1016/j.agrformet.2003.11.006, 2004.

Banimahd, S., and Khalili, D.: Factors Influencing Markov Chains Predictability Characteristics, Utilizing SPI, RDI, EDI and SPEI Drought Indices in Different Climatic Zones, Water Resources Management, 27, 3911-3928, 10.1007/s11269-013-0387-z, 2013.

Bell, L. C.: Establishment of native ecosystems after mining — Australian experience across diverse biogeographic zones, Ecological Engineering, 17, 179-186, http://dx.doi.org/10.1016/S0925-8574(00)00157-9, 2001.

Blum, A.: Crop responses to drought and the interpretation of adaptation, Plant Growth Regulation, 20, 135-148, 1996.

Bolger, T. P., Rivelli, A. R., and Garden, D. L.: Drought resistance of native and introduced perennial grasses of south-eastern Australia, Australian Journal of Agricultural Research, 56, 1261-1267, http://dx.doi.org/10.1071/AR05075, 2005.

Bot, A., and Benites, J.: The importance of soil organic matter: key to drought-resistant soil and sustained food and production, FAO, 2005.

Brouwers, N., Matusick, G., Ruthrof, K., Lyons, T., and Hardy, G.: Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem, Landscape Ecol, 28, 69-80, 10.1007/s10980-012-9815-3, 2013.

Bureau of Meteorology, Climate data: http://www.bom.gov.au/climate/data/, access: April, 2013.

Bureau of Meteorology, Australian Water Availability Project 2014 http://www.bom.gov.au/jsp/awap/, access: January, 2014.

Burton, M., Jasmine Zahedi, S., and White, B.: Public preferences for timeliness and quality of mine site rehabilitation. The case of bauxite mining in Western Australia, Resources Policy, 37, 1-9, 2012.

Chebbi, A., Bargaoui, Z. K., and Cunha, M. D.: Development of a method of robust rain gauge network optimization based on intensity-duration-frequency results, Hydrology and Earth System Sciences, 17, 4259-4268, 10.5194/hess-17-4259-2013, 2013.

Clark, C.: Measurements of actual and pan evaporation in the upper Brue catchment UK: the first 25 years, Weather, 68, 200-208, 10.1002/wea.2090, 2013.

Craven, D., Hall, J. S., Ashton, M. S., and Berlyn, G. P.: Water-use efficiency and whole-plant performance of nine tropical tree species at two sites with contrasting water availability in Panama, Trees-Structure and Function, 27, 639-653, 10.1007/s00468-012-0818-0, 2013.

Dajcman, S.: Tail dependence between Central and Eastern European and major European stock markets: a copula approach, Applied Economics Letters, 20, 1567-1573, 10.1080/13504851.2013.829185, 2013.

Darshana, Pandey, A., and Pandey, R. P.: Analysing trends in reference evapotranspiration and weather variables in the Tons River Basin in Central India, Stoch Environ Res Risk Assess, 27, 1407-1421, 10.1007/s00477-012-0677-7, 2013.

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, Agriculture, Ecosystems & Environment, 163, 85-93, http://dx.doi.org/10.1016/j.agee.2012.04.022, 2012.

Doley, D., and Audet, P.: Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites, Ecol Process, 2, 1-11, 10.1186/2192-1709-2-22, 2013.

Edwards, D. C.: Characteristics of 20th Century drought in the United States at multiple time scales, DTIC Document, AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH, 1997.

Egidijus, R., Edvinas, S., Vladimir, K., Justas, K., Gintaras, V., and Aliaksandr, P.: Dynamics of meteorological and hydrological droughts in the Neman river basin, Environmental Research Letters, 8, 045014, 10.1088/1748-9326/8/4/045014, 2013.

Engelbrecht, B. M., Comita, L. S., Condit, R., Kursar, T. A., Tyree, M. T., Turner, B. L., and Hubbell, S. P.: Drought sensitivity shapes species distribution patterns in tropical forests, Nature, 447, 80-82, 2007.

Ganguli, P., and Reddy, M. J.: Risk Assessment of Droughts in Gujarat Using Bivariate Copulas, Water Resource Management, 26, 3301–3327, 2012.

Gardner, J. H., and Bell, D. T.: Bauxite Mining Restoration by Alcoa World Alumina Australia in Western Australia: Social, Political, Historical, and Environmental Contexts, Restoration Ecology, 15, S3-S10, 10.1111/j.1526-100X.2007.00287.x, 2007.

Genest, C., and Rivest, L. P.: Statistical inference procedures for bivariate Archimedean copulas, Journal of the American statistical Association, 88, 1034-1043, 1993.

Guttman, N. B.: ACCEPTING THE STANDARDIZED PRECIPITATION INDEX: A CALCULATION ALGORITHM1, JAWRA Journal of the American Water Resources Association, 35, 311-322, 1999.

Hailegeorgis, T. T., Thorolfsson, S. T., and Alfredsen, K.: Regional frequency analysis of extreme precipitation with consideration of uncertainties to update IDF curves for the city of Trondheim, Journal of Hydrology, 498, 305-318, http://dx.doi.org/10.1016/j.jhydrol.2013.06.019, 2013.

Heim, R. R.: A Review of Twentieth-Century Drought Indices Used in the United States, Bulletin of the American Meteorological Society, 83, 1149-1165, 2002.

Hilhorst, H. W.: A critical update on seed dormancy. I. Primary dormancy, Seed Science Research, 5, 61-73, 1995.

Hinz, C., McGrath, G., and Hearman, A.: Towards a Climate Based Risk Assessment of Land Rehabilitation, 1st International Seminar on Mine Closure, Australian Centre for Geomechanics, Perth, 2006, 407-416.

Hodgkinson, J. H., Littleboy, A., Howden, M., Moffat, K., and Loechel, B.: Climate adaptation in the Australian mining and exploration industries., CSIRO Climate Adaptation National Research Flagship,1921605812 - working paper No. 5. http://www.csiro.au/resources/CAF-working-papers.html 2010.

Hu, Y.-M., Liang, Z.-M., Liu, Y.-W., Wang, J., Yao, L., and Ning, Y.: Uncertainty analysis of SPI calculation and drought assessment based on the application of Bootstrap, International Journal of Climatology, n/a-n/a, 10.1002/joc.4091, 2014.

Huang, M., Barbour, S. L., Elshorbagy, A., Zettl, J., and Si, B. C.: Effects of variably layered coarse textured soils on plant available water and forest productivity, in: Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges, edited by: Romano, N., Durso, G., Severino, G., Chirico, G. B., and Palladino, M., Procedia Environmental Sciences, Elsevier Science Bv, Amsterdam, 148-157, 2013.

Hutchinson, M. F., McIntyre, S., Hobbs, R. J., Stein, J. L., Garnett, S., and Kinloch, J.: Integrating a global agro-climatic classification with bioregional boundaries in Australia, Global Ecology and Biogeography, 14, 197-212, 2005.

Jacobs, S. J., Pezza, A. B., Barras, V., Bye, J., and Vihma, T.: An analysis of the meteorological variables leading to apparent temperature in Australia: Present climate, trends, and global warming simulations, Global and Planetary Change, 107, 145-156, 10.1016/j.gloplacha.2013.05.009, 2013.

Jahantab, E., Javdani, Z., Bahari, A., Bahrami, S., and Mehrabi, A.: Effect of priming treatments on seed germination percentage and rate in the early stages of triticale plants grown under drought stress conditions, International Journal of Agriculture and Crop Sciences (IJACS), 5, 1909-1917, IJACS/2013/5-17/1909-1917, 2013.

Joe, H.: Multivariate models and dependence concepts, Chapman & Hall, London, 1997.

Jongen, M., Unger, S., Fangueiro, D., Cerasoli, S., Silva, J. M. N., and Pereira, J. S.: Resilience of montado understorey to experimental precipitation variability fails under severe natural drought, Agriculture, Ecosystems & Environment, 178, 18-30, http://dx.doi.org/10.1016/j.agee.2013.06.014, 2013.

Khare, Y. P., Martinez, C. J., and Munoz-Carpena, R.: Parameter Variability and Drought Models: A Study Using the Agricultural Reference Index for Drought (ARID), Agronomy Journal, 105, 1417-1432, 10.2134/agronj2013.0167, 2013.

Khedun, C. P., Chowdhary, H., Mishra, A. K., Giardino, J. R., and Singh, V. P.: Water Deficit Duration and Severity Analysis Based on Runoff Derived from Noah Land Surface Model, Journal of Hydrologic Engineering, 18, 817-833, 2013.

Kuo, C. C., Gan, T. Y., and Chan, S.: Regional Intensity-Duration-Frequency Curves Derived from Ensemble Empirical Mode Decomposition and Scaling Property, Journal of Hydrologic Engineering, 18, 66-74, 10.1061/(asce)he.1943-5584.0000612, 2013.

Kuster, T., Arend, M., Bleuler, P., Günthardt-Goerg, M., and Schulin, R.: Water regime and growth of young oak stands subjected to air-warming and drought on two different forest soils in a model ecosystem experiment, Plant Biology, 15, 138-147, 2013.

Lebrun, R., and Dutfoy, A.: An innovating analysis of the Nataf transformation from the copula viewpoint, Probabilistic Engineering Mechanics, 24, 312-320, http://dx.doi.org/10.1016/j.probengmech.2008.08.001, 2009.

Lee, T., Modarres, R., and Ouarda, T. B. M. J.: Data-based analysis of bivariate copula tail dependence for drought duration and severity, Hydrological Processes, 27, 1454-1463, Doi 10.1002/Hyp.9233, 2013.

Li, T. Y., Guo, S. L., Chen, L., and Guo, J. L.: Bivariate Flood Frequency Analysis with Historical Information Based on Copula, Journal of Hydrologic Engineering, 18, 1018-1030, 10.1061/(asce)he.1943-5584.0000684, 2013.

Li, Z., Chen, Y. N., Yang, J., and Wang, Y.: Potential evapotranspiration and its attribution over the past 50 years in the arid region of Northwest China, Hydrological Processes, 28, 1025-1031, 2014.

Liu, C.-L., Zhang, Q., Singh, V. P., and Cui, Y.: Copula-based evaluations of drought variations in Guangdong, South China, Natural hazards, 59, 1533-1546, 2011.

Lloret, F.: Vulnerability and resilience of forest ecosystems to extreme drought episodes., Ecosistemas, 21, 85-90, 2012.

Loaiciga, H., and Mariño, M.: Recurrence Interval of Geophysical Events, Journal of Water Resources Planning and Management, 117, 367-382, doi:10.1061/(ASCE)0733-9496(1991)117:3(367), 1991.

Lugato, E., Alberti, G., Gioli, B., Kaplan, J. O., Peressotti, A., and Miglietta, F.: Long-term pan evaporation observations as a resource to understand the water cycle trend: case studies from Australia, Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 58, 1287-1296, 10.1080/02626667.2013.813947, 2013.

Madadgar, S., and Moradkhani, H.: Drought analysis under climate change using copula, Journal of Hydrologic Engineering, 746–759, 10.1061/(ASCE)HE.1943-5584.0000532, 2011.

Mariotte, P., Vandenberghe, C., Kardol, P., Hagedorn, F., and Buttler, A.: Subordinate plant species enhance community resistance against drought in semi-natural grasslands, Journal of Ecology, 101, 763-773, 10.1111/1365-2745.12064, 2013.

Mason, L., Corinne Unger, Aleta Lederwasch, Hala Razian, Laura Wynne, and Damien Giurco: Adapting to climate risks and extreme weather: A guide for mining and minerals industry professionals, National Climate Change Adaptation Research Facility , Gold Coast,, 76 pp. , 2013.

McKee, T. B., Doesken Nolan J, and Kleist John: The relationship of drought frequency and duration to time scales, Proceedings of the 8th Conference on Applied Climatology, Anaheim, California, 1993, 179-183.

Mirabbasi, R., Fakheri-Far, A., and Dinpashoh, Y.: Bivariate drought frequency analysis using the copula method, Theoretical and Applied Climatology, 108, 191-206, 2012.

Mishra, A. K., and Singh, V. P.: A review of drought concepts, Journal of Hydrology, 391, 202–216, 2010.

Murphy, B. F., and Timbal, B.: A review of recent climate variability and climate change in southeastern Australia, International Journal of Climatology, 28, 859-879, 10.1002/joc.1627, 2008.

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

National Drought Mitigation Cente-Interpretation of Standardized Precipitation Index Maps: http://drought.unl.edu/MonitoringTools/ClimateDivisionSPI/Interpretation.aspx, access: January, 2014.

Nefzaoui, A., and Ben Salem, H.: Cacti: Efficient tool for rangeland rehabilitation, drought mitigation and to combat desertification, in: Proceedings of the Fourth International Congress on Cactus Pear and Cochineal, edited by: Nefzaoui, A., and Inglese, P., Acta Horticulturae, 581, 295-315, 2002.

Passioura, J.: The drought environment: physical, biological and agricultural perspectives, Journal of experimental Botany, 58, 113-117, 2007.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633-1644, 10.5194/hess-11-1633-2007, 2007.

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., and Solomon, A. M.: Special Paper: A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate, Journal of Biogeography, 19, 117-134, 10.2307/2845499, 1992.

Quiring, S. M.: Monitoring Drought: An Evaluation of Meteorological Drought Indices, Geography Compass, 3, 64-88, 10.1111/j.1749-8198.2008.00207.x, 2009.

Reddy, M. J., and Ganguli, P.: Application of copulas for derivation of drought severity-duration-frequency curves, Hydrological Processes, 26, 1672-1685, 10.1002/hyp.8287, 2012.

Ruffault, J., Martin-StPaul, N., Rambal, S., and Mouillot, F.: Differential regional responses in drought length, intensity and timing to recent climate changes in a Mediterranean forested ecosystem, Climatic Change, 117, 103-117, 10.1007/s10584-012-0559-5, 2013.

Shi, Z., Thomey, M. L., Mowll, W., Litvak, M., Brunsell, N. A., Collins, S. L., Pockman, W. T., Smith, M. D., Knapp, A. K., and Luo, Y.: Differential effects of extreme drought on production and respiration: synthesis and modeling analysis, Biogeosciences, 11, 621-633, 10.5194/bg-11-621-2014, 2014.

Shiau, J.-T., Feng, S., and Nadarajah, S.: Assessment of hydrological droughts for the Yellow River, China, using copulas, Hydrological Processes, 21, 2157-2163, 10.1002/hyp.6400, 2007.

Shiau, J.-T., Modarres, R., and Nadarajah, S.: Assessing Multi-site Drought Connections in Iran Using Empirical Copula, Environ Model Assess, 17, 469-482, 10.1007/s10666-012-9318-2, 2012.

Shiau, J. T., and Shen, H.: Recurrence Analysis of Hydrologic Droughts of Differing Severity, Journal of Water Resources Planning and Management, 127, 30-40, doi:10.1061/(ASCE)0733-9496(2001)127:1(30), 2001.

Shiau, J. T.: Fitting Drought Duration and Severity with Two-Dimensional Copulas, Water Resources Management, 20, 795–815, 2006.

Shiau, J. T., and Modarres, R.: Copula-based drought severity-duration-frequency analysis in Iran, Meteorological Applications, 16, 481-489, 10.1002/met.145, 2009.

Sklar, M.: Fonctions de répartition à n dimensions et leurs marges, Université Paris, Paris, 229–231 pp., 1959.

Smithers, J., Pegram, G., and Schulze, R.: Design rainfall estimation in South Africa using Bartlett–Lewis rectangular pulse rainfall models, Journal of Hydrology, 258, 83-99, 2002.

Spinoni, J., Antofie, T., Barbosa, P., Bihari, Z., Lakatos, M., Szalai, S., Szentimrey, T., and Vogt, J.: An overview of drought events in the Carpathian Region in 1961–2010, Advances in Science and Research 10, 21-32, 10.5194/asr-10-21-2013, 2013.

Sternberg, M., and Shoshany, M.: Influence of slope aspect on Mediterranean woody formations: Comparison of a semiarid and an arid site in Israel, Ecological Research, 16, 335-345, 10.1046/j.1440-1703.2001.00393.x, 2001.

Tsakiris, G.: Meteorological Drought Assessment., European Research Program MEDROPLAN (Mediterranean Drought Preparedness and Mitigation Planning), Zaragoza, Spain, 2004.

Tsakiris, G., and Vangelis, H.: Establishing a drought index incorporating evapotranspiration European water 9/10, 3-11, 2005.

Tsakiris, G., D. Pangalou, and H. Vangelis: Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI), Water Resource Management, 21, 821–833, 2007.

UNEP, U. N. E. P.: World Atlas of Desertification, London, 1992.

Vangelis, H., Tigkas, D., and Tsakiris, G.: The effect of PET method on Reconnaissance Drought Index (RDI) calculation, Journal of Arid Environments, 88, 130-140, http://dx.doi.org/10.1016/j.jaridenv.2012.07.020, 2013.

Vargas, R., Sonnentag, O., Abramowitz, G., Carrara, A., Chen, J. M., Ciais, P., Correia, A., Keenan, T. F., Kobayashi, H., and Ourcival, J.-M.: Drought Influences the Accuracy of Simulated Ecosystem Fluxes: A Model-Data Meta-analysis for Mediterranean Oak Woodlands, Ecosystems, 16, 749–764, 2013.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696-1718, 10.1175/2009JCLI2909.1, 2010.

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., and Sanchez-Lorenzo, A.: Response of vegetation to drought time-scales across global land biomes, Proceedings of the National Academy of Sciences, 110, 52-57, 10.1073/pnas.1207068110, 2013.

Wang, Y. C., Wu, J. L., and Lai, Y. H.: A revisit to the dependence structure between the stock and foreign exchange markets: A dependence-switching copula approach, Journal of Banking & Finance, 37, 1706-1719, 10.1016/j.jbankfin.2013.01.001, 2013.

Wilhite, D. A., Svoboda, M. D., and Hayes, M. J.: Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness, Water resources management, 21, 763-774, 2007.

Williams, J., Hook, R., and Hamblin, A.: Agro-ecological regions of Australia methodology for their derivation and key issues in resource management.,(CSIRO Land & Water, 0643060979: Canberra, ACT), 2002.

Williamson, G. B., Laurance, W. F., Oliveira, A. A., Delamônica, P., Gascon, C., Lovejoy, T. E., and Pohl, L.: Amazonian tree mortality during the 1997 El Nino drought, Conservation Biology, 14, 1538-1542, 2000.

Woli, P., Jones, J. W., Ingram, K. T., and Fraisse, C. W.: Agricultural reference index for drought (ARID), Agronomy Journal, 104, 287-300, 2012.

Wong, G., Lambert M. F., Leonard M., and Metcalfe A. V.: Drought Analysis Using Trivariate Copulas Conditional on Climatic States, Journal Of Hydrologic Engineering, 15, 129-141, 2010.

Woodhams, F., Southwell, D., Bruce, S., Barnes, B., Appleton, H., Rickards, J., Walcott, J., Hug, B., Whittle, L., and Ahammad, H.: Carbon Farming Initiative: A proposed common practice framework for assessing additionality, Canberra, August, 2012.

Yoo, J., Kim, U., and Kim, T.-W.: Bivariate drought frequency curves and confidence intervals: a case study using monthly rainfall generation, Stoch Environ Res Risk Assess, 27, 285-295, 2013.

Zargar, A., Sadiq, R., Naser, B., and Khan, F. I.: A review of drought indices, Environmental Reviews, 19, 333-349, 2011.

Zhang, A., and Jia, G.: Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data, Remote Sensing of Environment, 134, 12-23, http://dx.doi.org/10.1016/j.rse.2013.02.023, 2013.

Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resources Research, 37, 701-708, 10.1029/2000WR900325, 2001.

Zhang, Q., Chen, Y. D., Chen, X., and Li, J.: Copula-based analysis of hydrological extremes and implications of hydrological behaviors in the Pearl River basin, China, Journal of Hydrologic Engineering, 16, 598-607, 2011.

Table 1. Climate indices and classification of selected locations across eastern Australia with focus on rainfall.

Location	**Length of meteorological data (years)**	**Climate index**		**Climate classification system**			
		R/PET[a]	**R_w/R_s**[b]	**Köppen-Geiger**[c]	**Australian Agricultural Environment**[d]	**Agro-climatic**[e]	**potential productive landuse**[e,d]
Weipa	1960-1994 (34)	0.99	0.01	Aw – Tropical, savannah	AAE1 – Tropics (wet/dry season)	I1 – wet/dry season (temporally water-limited)	crops, rangeland
Cairns	1965-2013 (48)	0.91	0.10	Aw – Tropical, savannah	AAE2 – Tropical coast (wet)	I3 – wet/dry season (temporally water-limited)	crops, rangeland, sugarcane
Brisbane	1986-2013 (27)	0.55	0.38	Cfa – Temperate, without dry season	AAE6 – Subtropical coast (wet)	F4 – wet	horticulture, pasture, sugarcane
Sydney	1970-1994 (24)	0.53	0.51	Cfb – Temperate, without dry season	AAE10 - Temperate coast east (wet, winter-dominant rainfall)	F3 – wet	crops, horticulture, pasture
Melbourne	1955-2013 (58)	0.51	0.95	Cfb – Temperate, without dry season	AAE10 - Temperate coast east (wet, winter-dominant rainfall)	D5 – wet (moderately water-limited in summer)	crops, forestry, horticulture, pasture
Kingaroy	1967-2001 (34)	0.47	0.34	Cfa – Temperate, without dry season	AAE7 - Wheatbelt downs (summer-dominant/moderate rainfall)	E4 – water-limited	cotton, crops, pasture,
Brigalow Research Station	1968-2011 (43)	0.32	0.27	Cfa – Temperate, without dry season	AAE4 – Subtropical plains (summer-dominant/moderate rainfall)	E4 – water-limited	
Wagga Wagga	1966-2013 (47)	0.30	1.21	Cfb – Temperate, without dry season	AAE14 – Wheatbelt east (winter-dominant rainfall)	E3 – water-limited in summer	crops, horticulture, pasture
Bourke	1967-1996 (29)	0.20	0.61	BSh – Arid, steppe	AAE18 – Arid (dry)	E6 – water-limited	rangeland, wildland
Quilpie	1970-2013 (43)	0.14	0.36	BSh – Arid, steppe	AAE18 – Arid (dry)	H – water-limited	
Mount Isa	1975-2013 (38)	0.13	0.05	BSh – Arid, steppe	AAE18 – Arid (dry)	G – water-limited	

a – (UNEP, 1992)
b – Based on average of three months of rainfall during winter (June – August) and summer (December – February)
c –(Peel et al., 2007)
d –(Woodhams et al., 2012)
e – (Hutchinson et al., 2005)

Table 2. Mean severity μ_S and duration μ_D of selected locations across eastern Australia, and corresponding coefficient of variation CV_S and CV_D for short-term (RDI_3) and long-term ($SPEI_{12}$) droughts.

Location	**RDI_3**				**$SPEI_{12}$**			
	μ_S	**CV_S**	**μ_D**	**CV_D**	**μ_S**	**CV_S**	**μ_D**	**CV_D**
Weipa	5.2	0.2	5.8	0.1	8.4	1.1	10.4	0.8
Cairns	4.7	0.4	6.4	0.3	9.6	1.3	12.5	1.0
Brisbane	3.1	3.3	3.6	0.8	11.2	0.9	13.3	0.8
Sydney	3.4	0.9	4.4	0.6	6.5	1.7	8.9	0.9
Melbourne	4.5	0.7	5.8	0.5	14.5	1.9	18.6	1.6
Kingaroy	2.8	1.2	3.7	0.8	7.0	1.1	8.3	0.8
Brigalow Research Station	3.4	1.0	4.4	0.9	8.0	1.3	10.2	1.0
Wagga Wagga	5.2	0.8	6.2	0.6	8.6	1.8	13.8	1.1
Bourke	2.8	3.9	3.9	1.1	8.2	2.0	9.9	1.5
Quilpie	3.5	1.1	4.6	0.7	18.8	2.1	21.8	1.5
Mount Isa	3.8	0.7	4.9	0.5	11.1	1.2	14.4	0.9

Table 3. Management actions for addressing specific kinds of drought characteristics identified with SDF curves for the southern hemisphere.

Management domain	Management actions	Type of drought
Plant species selection	Drought tolerant species	LS, LP, SP, SS
	Quickly germinating species	SS
	Species with physical/chemical dormancy	LS, LP
	Shade tolerant species on southern aspects	LS, LP
	Light tolerant species on northern aspects	LS, LP, SP, SS
	Annual grasses	SS, SP
	Perennial grasses	LS, LP, SP, SS
	Trees	LS, LP
Planting/seeding regime	Trees require repeated establishment	LS, LP
	Annual/perennial grasses are successful after rain events	SS, SP
Soil characteristics	Deep top soil	LS, LP, SP
	Amendments of silt/clay	LS, LP
	Gentle slopes	LS, LP
	Mulching	SS
Irrigation method	Regular irrigation	LS, LP
	Seasonal irrigation	SS, SP
	Critical stage irrigation	LS,LP,SP,SS
	Drainage system	LS, LP

SS – High recurrence of short time scale (3 month) severe droughts
SP – High recurrence of short time scale (3 month) prolonged droughts
LS – High recurrence of long time scale (12 months) severe droughts
LP – High recurrence of long time scale (12 months) prolonged droughts

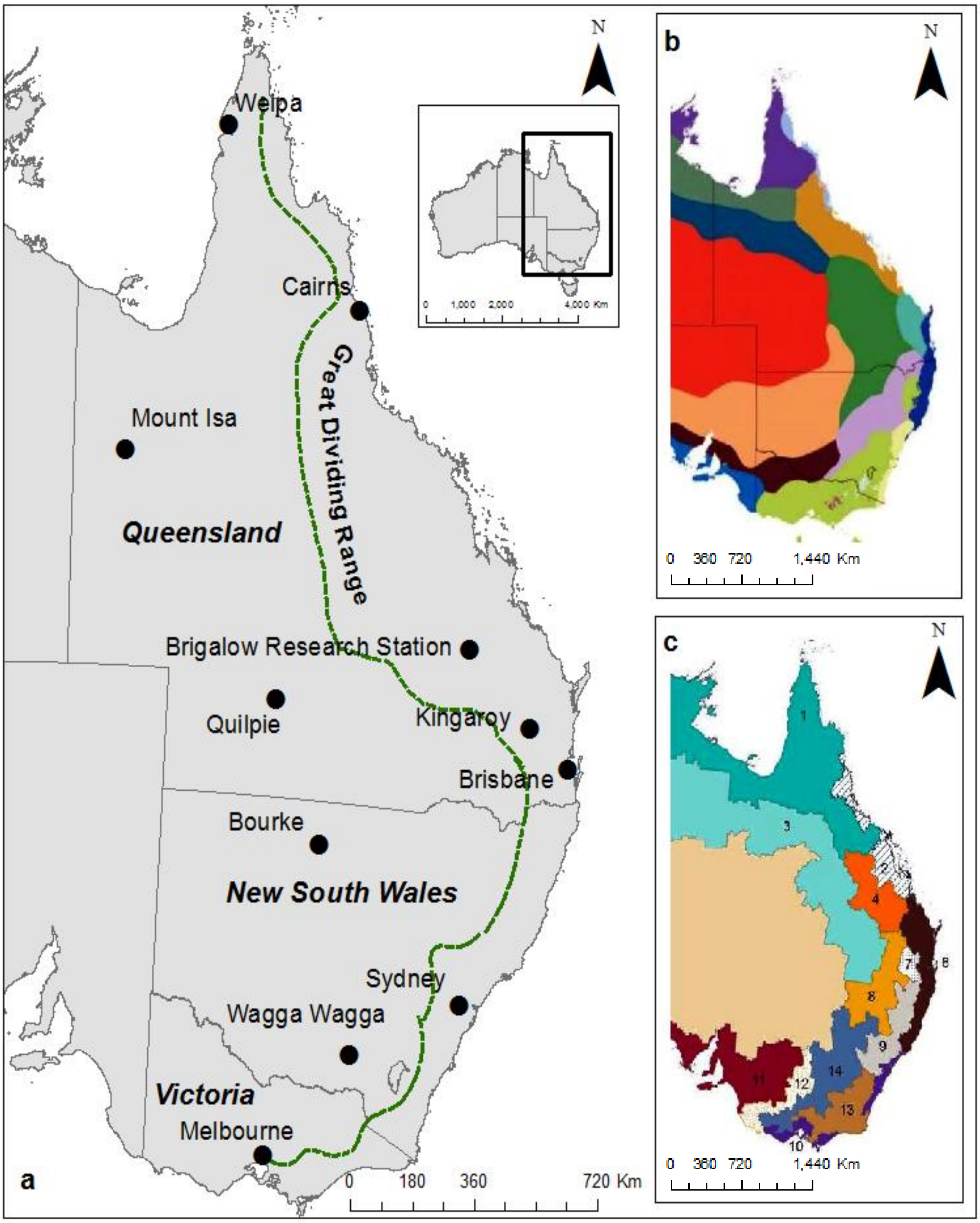
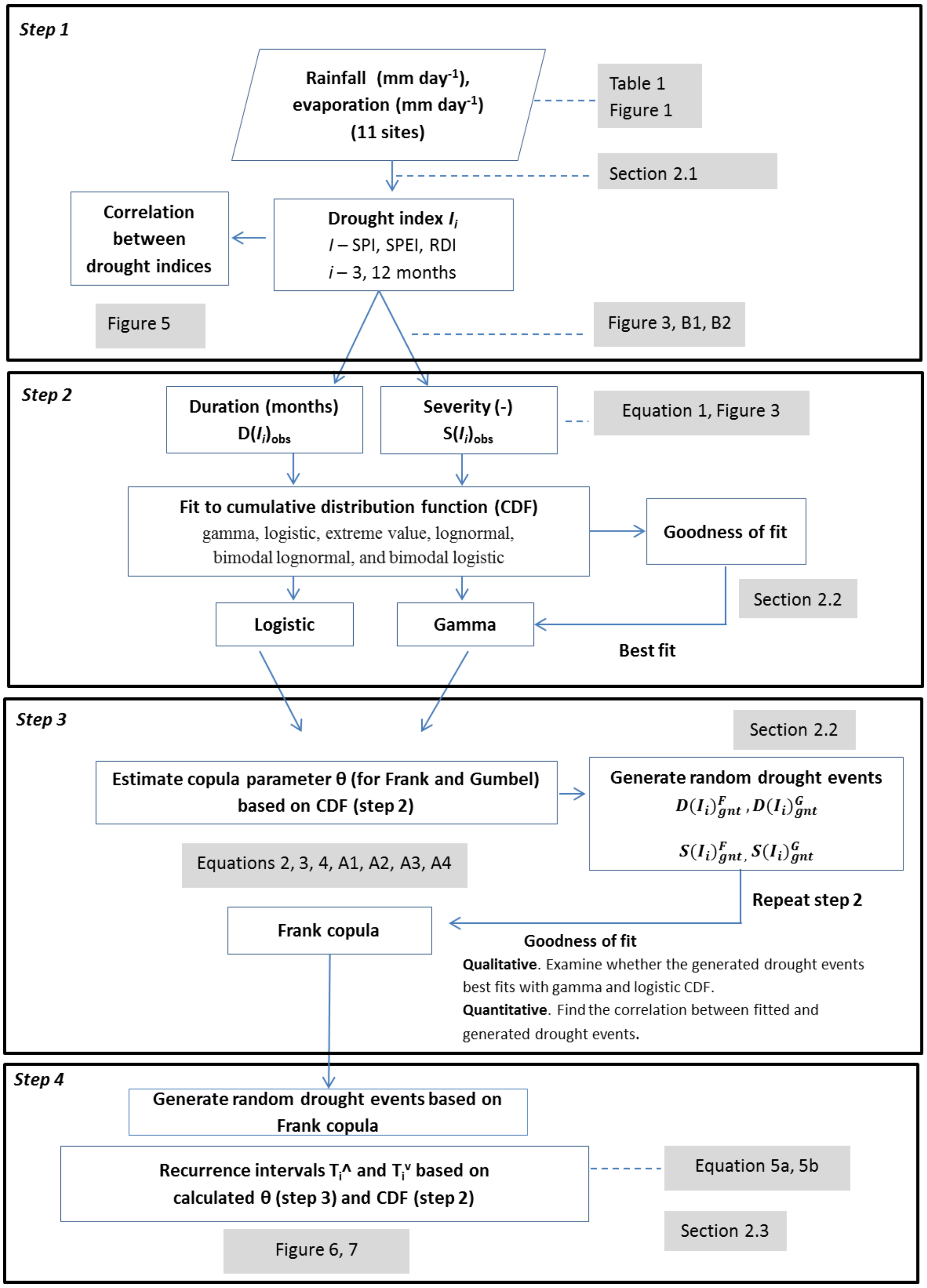


Figure 1. (a) Selected locations of interest with boundaries of (b) agro-climatic classes (Hutchinson et al., 2005) and (c) Australian agricultural environments (Woodhams et al., 2012).



F-Frank copula, G-Gumbel copula, gnt-generated

Figure 2. Schematic diagram of steps applied to estimate recurrence intervals of drought events. See Section 2 for further details. *Step 1.* Calculate drought index based on monthly rainfall (SPI) and evaporation (RDI, SPEI). *Step 2.* Fit cumulative distribution function (CDF) to estimated drought duration and severity. *Step 3.* Estimate copula parameter based on CDFs. *Step 4.* Calculate recurrence intervals based on CDFs of univariate (severity, duration) distributions and bivariate joint distribution (copula).

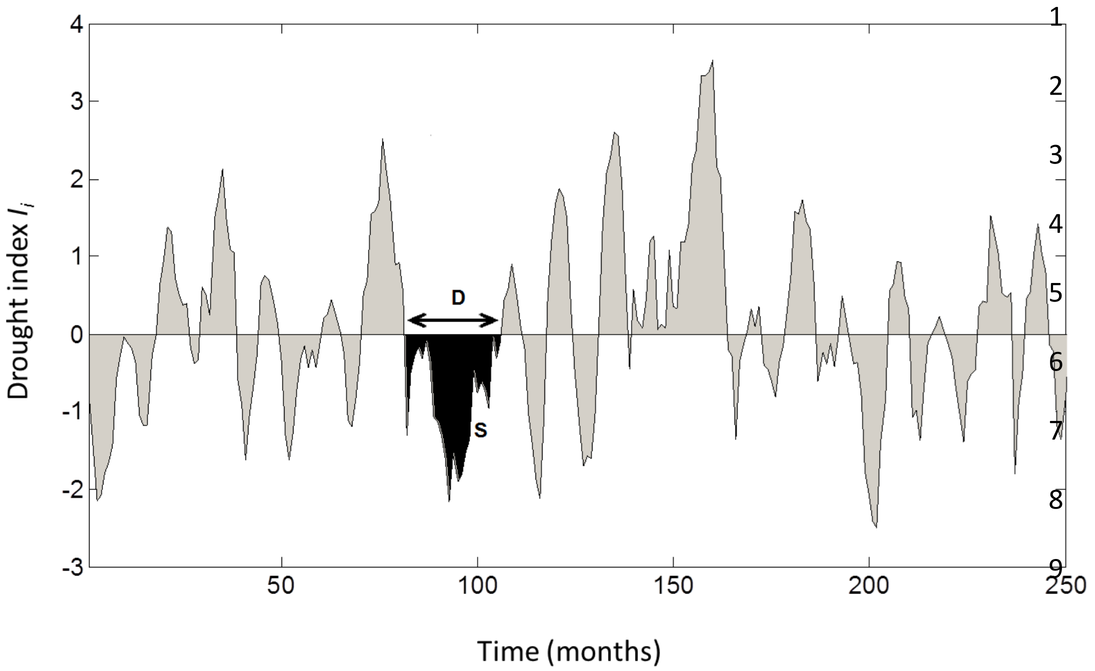


Figure 3. Concept of severity S and duration D of a drought event quantified with drought index I_i, where i refers to any time-scale of interest.

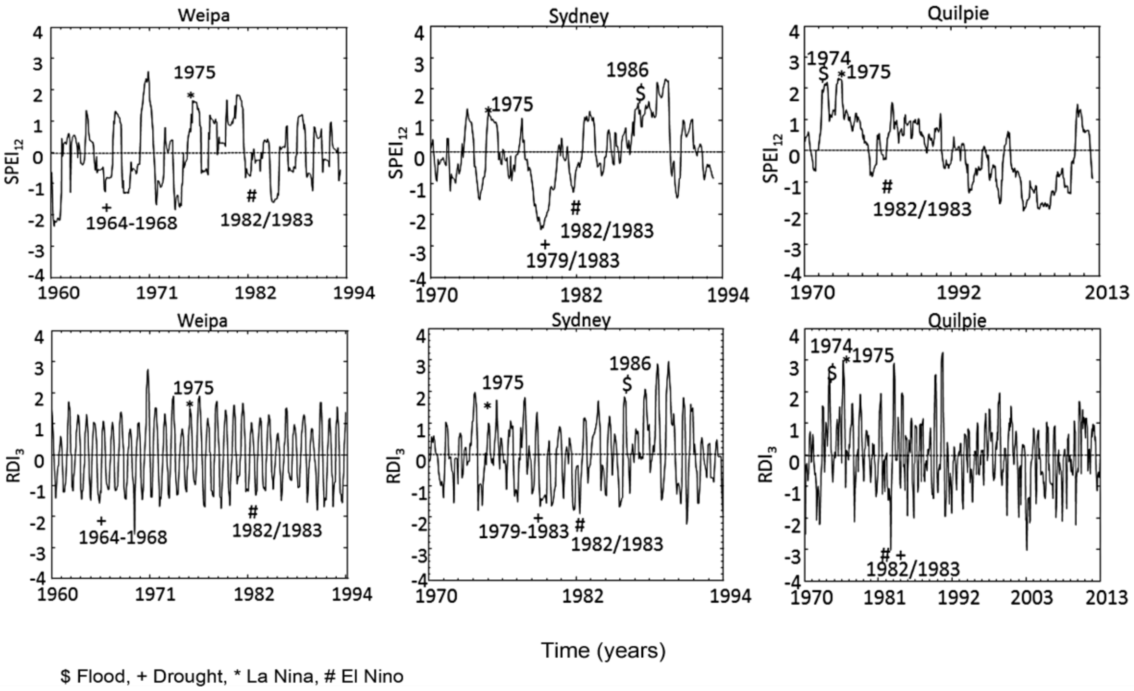


Figure 4. Calculated SPEI$_{12}$ (upper row) and RDI$_{3}$ (lower row) for Weipa, Sydney and Quilpie including major weather events. The same indices are depicted for all other selected locations in Appendix B.

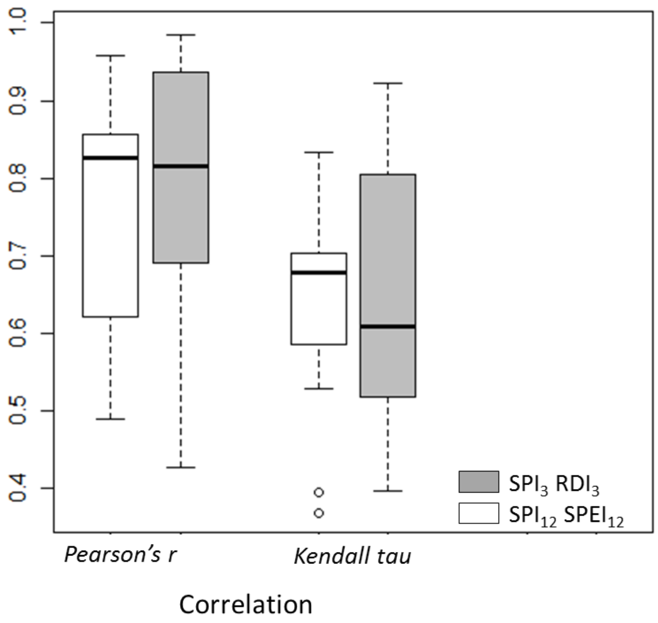


Figure 5. Correlation between SPI_3 and RDI_3, and SPI_{12} and $SPEI_{12}$ based on the correlation coefficient Pearson's r and Kendall tau. The outliers represent the very dry locations of Bourke and Quilpie.

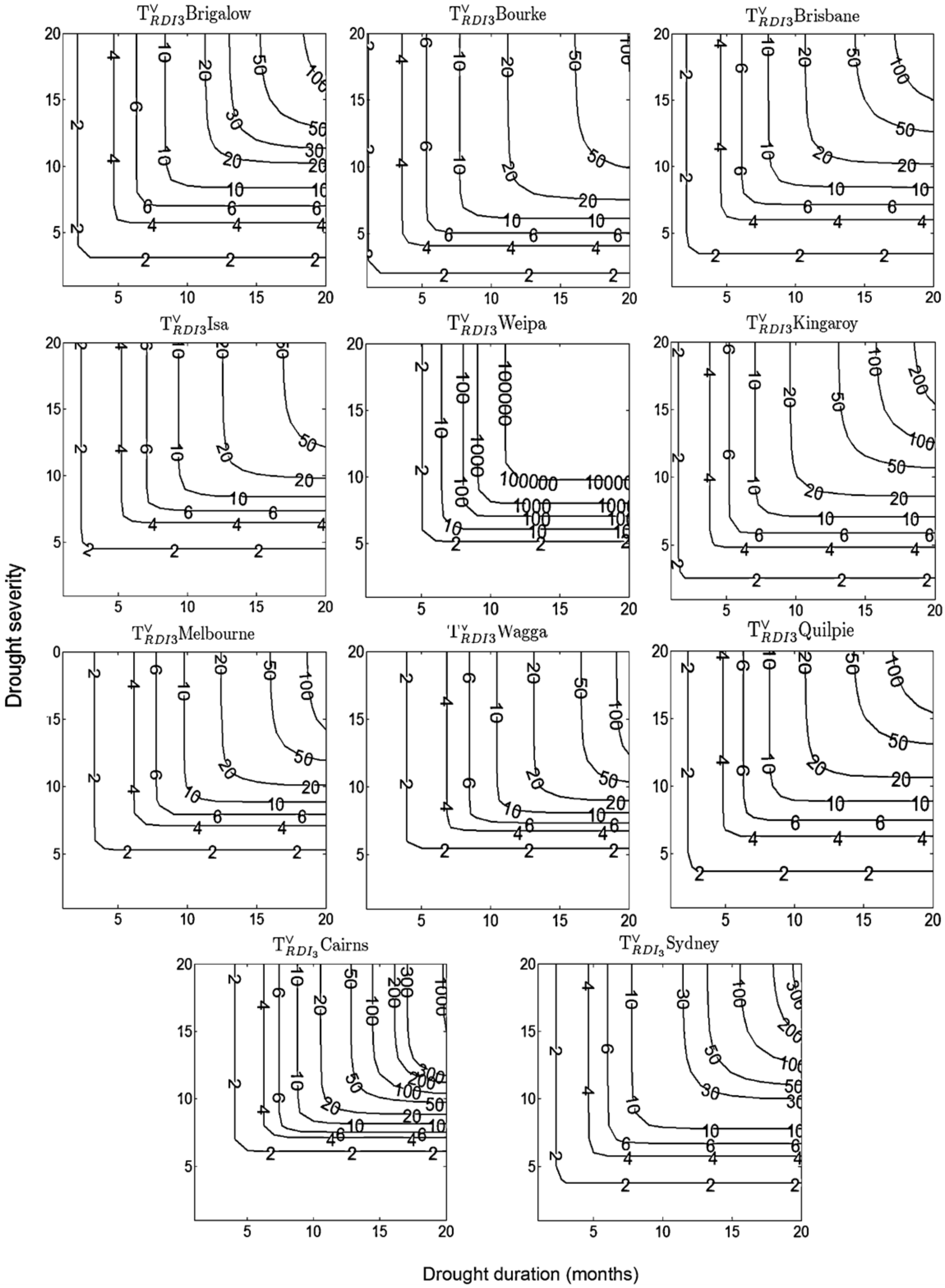


Figure 6. Recurrence interval T^v (years) of drought events of any severity *or* duration of interest based on the RDI_3 (short-term) of historical rainfall.

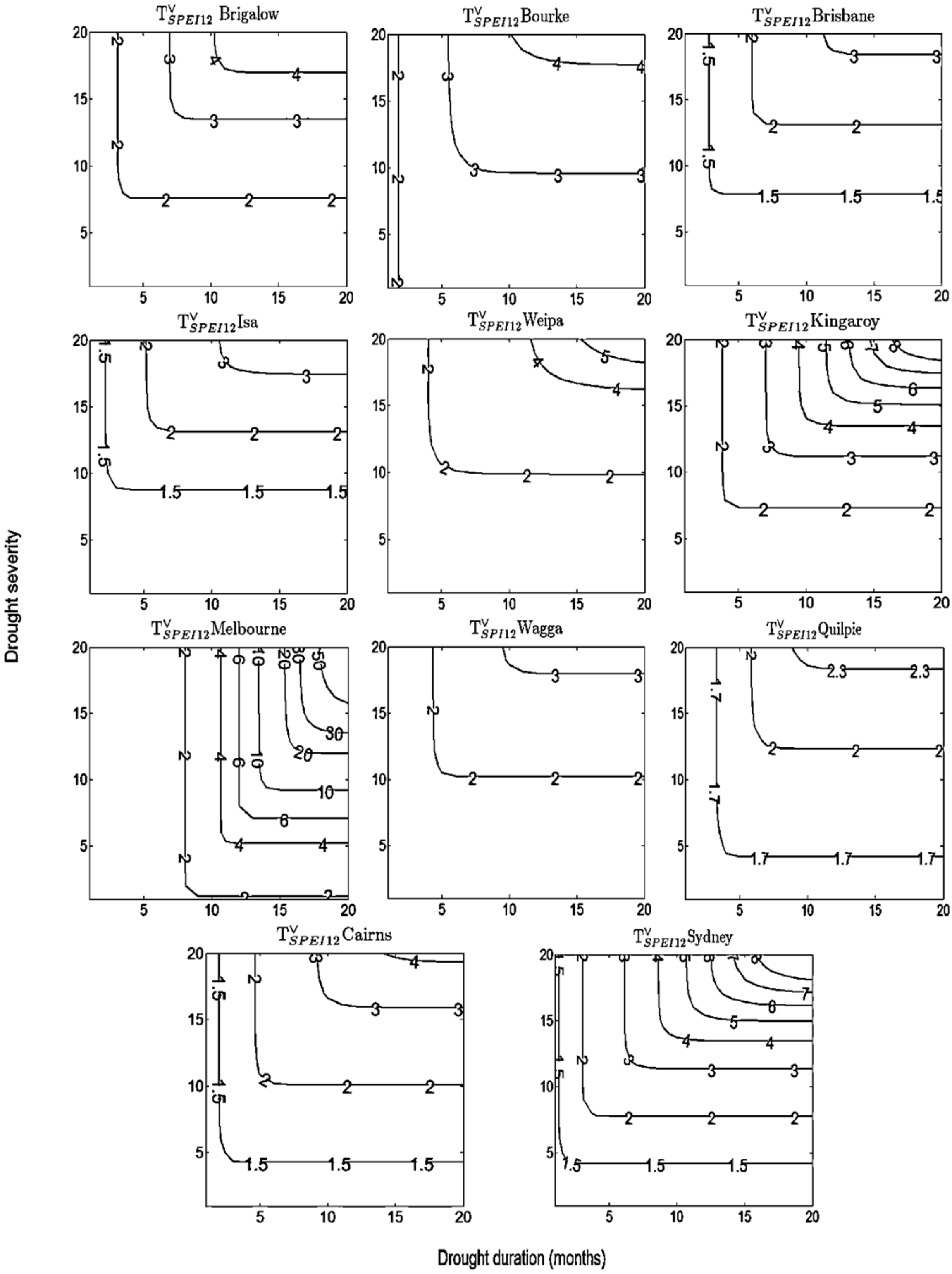


Figure 7. Recurrence interval T^{v} (years) of drought events of any severity *or* duration of interest based on $SPEI_{12}$ (long-term) of historical rainfall.