STAGE 1 | ENHANCED DROUGHT INFORMATION SYSTEM

NSW DPI Combined Drought Indicator

Technical Report

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More information

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- Dr John Sims (Senior Principal Scientist, Australian Bureau of Agricultural and Resource Economics and Sciences ABARES, Department of Agriculture and Water Resources);
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Foreword

NSW and Australia have always had a variable climate with extremes like drought having large economic, social and environmental impacts. Effective monitoring of drought can be used to mitigate the severe impacts of drought by supporting actions of farmers and government agencies. There is a global research effort dedicated to improving drought monitoring and the application of that information to public policy and planning. While Australia has generally opted for single meteorological indicators or agronomic indicators, an alternative approach is to accommodate competing definitions through the integration of multiple drought indicators.

This report describes the development of such an approach for NSW known as the Combined Drought Indicator (CDI). The CDI is a multi-indicator framework that objectively represents meteorological, hydrological and agronomic indices. Testing under Australian conditions across the State reveals that the CDI addresses many of the technical challenges to improved drought monitoring in Australia. Consistent application of the CDI will provide the NSW Government with the capacity to monitor drought more effectively, and consistent with improving drought preparedness, engage stakeholders constructively at key times.

The CDI is the main output of Stage 1 of NSW DPI’s Enhanced Drought Information System (EDIS). EDIS Integrates a range of soil, land use and climate data sets at a 5km resolution across the state to improve the accuracy, reliability and comprehensiveness of drought assessment, monitoring and early warning. This new analytical system was developed in response to findings from a review of seasonal conditions reporting which found that a more sophisticated staged approach to seasonal conditions assessment could be developed using comprehensive drought indices. Through initiatives like EDIS, the NSW Government is committed to working with industry and stakeholders to enhance farmers' drought preparedness and responses to drought.

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Abstract

Initially a conceptual framework was developed to classify drought into ‘Non Drought’, ‘Warning’, ‘Drought’, ‘Early Recovery’, and ‘Strong Recovery’ phases. The framework was then represented objectively using meteorological, hydrological and agronomic indices from an Enhanced Drought Information System (EDIS), resulting in the development of the Combined Drought Indicator (CDI). The CDI was also refined through several rounds of stakeholder engagement as it was being developed. The approach is similar to the current multi-indicator frameworks used in the United States and Europe. Testing under Australian conditions across the state of New South Wales reveals that the CDI addresses many of the technical aspects of the criticism that Australian drought monitoring and declaration has been ad-hoc and adversarial. Principally, the CDI resolves debates over multiple drought definitions, providing a repeatable basis for drought declaration. Using a simple Drought Direction Index (DDI), the CDI also provides a consistent approach to track drought entry and exit, which has been notoriously difficult under Australian conditions. In depth testing established that drought indicators are particularly sensitive to changes in their configuration, and incremental adjustments to them as part of past drought declaration processes were one likely source of the large, albeit unintended, consequences identified by other analysts. Consistent application of the CDI will provide the NSW Government with the capacity to monitor drought more effectively, and consistent with improving drought preparedness, engage stakeholders constructively at an appropriate time during a complex and difficult to define climatic event.

Introduction

Effective monitoring of drought can be used to mitigate the severe impact that it has on people, land and the economy, but unlike floods, storms and frosts, the onset and end of drought is insidious and its progression is highly uncertain (Stafford-Smith and McKeon 1998). Moreover, it is widely recognised that drought has multiple competing definitions and depending upon the context, 'drought' can be a meteorological, hydrological, agronomic or a socio-economic phenomenon (Wilhite et al. 2006; White and Walcott 2009; Howden 2014). Drought monitoring involves the construction of indicators to quantify these definitions, using complex information flows and analytical methods developed by experts, that stakeholders often find difficult to apply (Steinemann and Cavalcanti 2006). The challenge of drought monitoring is further compounded when considering how the meteorological and hydrological processes underpinning drought are evolving under a changing climate (Hennessey et al. 2009; Howden 2014; Sivakumar et al. 2014).

There is a global research effort dedicated to improving drought monitoring (Sivakumar et al. 2010; White and Bordas 1997; Kokic et al. 2007; White and Walcott 2009; Sivakumar et al. 2014), as well as the application of information from drought monitoring in public policy and planning, including drought declaration processes (Keogh 2015; Botterill 2003; Botterill and Hayes 2012; Howden 2014; Wilhite et al. 2000; Steinemann and Cavalcanti 2006; Stone 2014). One promising approach to accommodate competing definitions is to develop a framework that uses quantitative methods that integrate multiple drought indicators and information flows, such as the operational drought monitoring frameworks currently used by the United States (Svoboda et al. 2002) and Europe (Sepulcre et al. 2012). These frameworks provide a methodology to track drought conditions (de Jager and Vogt 2015; Cammalleri et al. 2015), but also integrate complex information into a simple form for use in management and public policy decision making (Svoboda et al. 2002). The European framework also provides monitoring information not just for in-drought conditions, but also for out-of-drought conditions like entry and recovery, to guide preparedness and provide early warning.

Australia has taken a different and arguably narrower approach to the challenges of drought monitoring. Current monitoring frameworks predominantly use single meteorological indicators (e.g. Australian Rainfall Deficiency Analyser[1]) and agronomic indicators (e.g. QDPI long paddock[2]), but there are also multi-indicator frameworks in use (e.g. NSW Drought Escalation Framework[3]). The key difference is that the focus of these frameworks is monitoring the severity of in-drought conditions mainly to partition between 'normal drought' and 'rare' or 'exceptional'

[1] http://www.bom.gov.au/climate/ada/
[2] https://www.longpaddock.qld.gov.au/
[3] http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/585708/NSW-Drought-Framework_web.pdf

events, and this information is used to 'trigger' drought declaration which, in turn, is linked to the provision of financial and other support for farmers. Other properties of drought, such as the timing of entry into, and recovery from an event, have proven more difficult to determine objectively (Stafford-Smith and Mckeon 1998; White and Walcott 2009). In contrast to international frameworks described above, the integration of individual drought indicators is a subjective task completed by expert committees in the declaration process. This general approach mirrors the Australia-wide Exceptional Circumstances drought declaration and support scheme which ran from 1990-2008, and was informed by a national multi-indicator drought assessment process (White and Bordas 1997).

Australian drought declaration and support systems that rely on drought monitoring have been heavily and broadly criticised at a policy and technical level (Botterill 2003; Hennessey et al. 2008; Productivity Commission 2008; PIMC 2011; Howden 2014; Keogh 2015). Within this broad ranging set of criticisms, there are five important observations that can be directly related to Australian drought monitoring frameworks. Firstly, they have not adequately addressed the challenges of reconciling multiple drought definitions and indicators (Botteril 2003). Secondly, because of the subjective approach to integration, incremental adjustments have been made to the frameworks during the decision making process, often without adequate testing or understanding of the implications (Botteril 2003; Botteril and Hayes 2012; Howden 2014), giving rise to periods of inconsistency in the drought declaration history, and correspondingly, inequitable provision of support to farmers (Productivity Commission 2008; Keogh 2015). Thirdly, there are difficulties with reconciling the regional environmental data that underpins drought monitoring with the need to ensure consistent and equitable declaration at the individual farm level (Botteril 2003; Botteril and Hayes 2012). Fourthly, the use of drought indicators that rely on ranking current conditions relative to past conditions to quantify severity may be problematic in a changing climate, where droughts could be more frequent and-or more severe (Hennessey et al. 2008). Finally, because the drought declaration process is 'evidentiary' and focused on partitioning 'moderate' from 'severe' drought which establishes well into a drought event, the burden of information collection falls on farmers at a highly stressful time when they should be focused on management (Botteril 2003). Collectively, these issues contribute to the adversarial nature of drought monitoring and declaration that characterises the Australian experience (Botteril 2003; Botteril and Hayes 2012; Howden 2014; Keogh 2015).

The multi-indicator frameworks used in other countries provide a promising model that could be adapted to address many of these criticisms, and to broaden the application of monitoring beyond its current focus on in-drought severity. As a step toward this, a conceptual multi-indicator framework called the Combined Drought Indicator (CDI) was developed and is presented in Figure 1(a). The framework illustrates the transition of climate between wetter and dryer states over time by partitioning a sequence of climate variability into generic phases including ‘Drought’, ‘Warning’, ‘Early Recovery’, ‘Strong Recovery’ and ‘Non Drought’. The variations in Figure 1(b) show how this conceptual framework could operate under some real sequences of climate variability for a selected location in NSW. While this multi-indicator framework provides an attractive conceptual model the question remains as to how to configure the approach for Australian conditions to address some of the criticisms that have been levelled at past drought monitoring efforts and declaration processes.

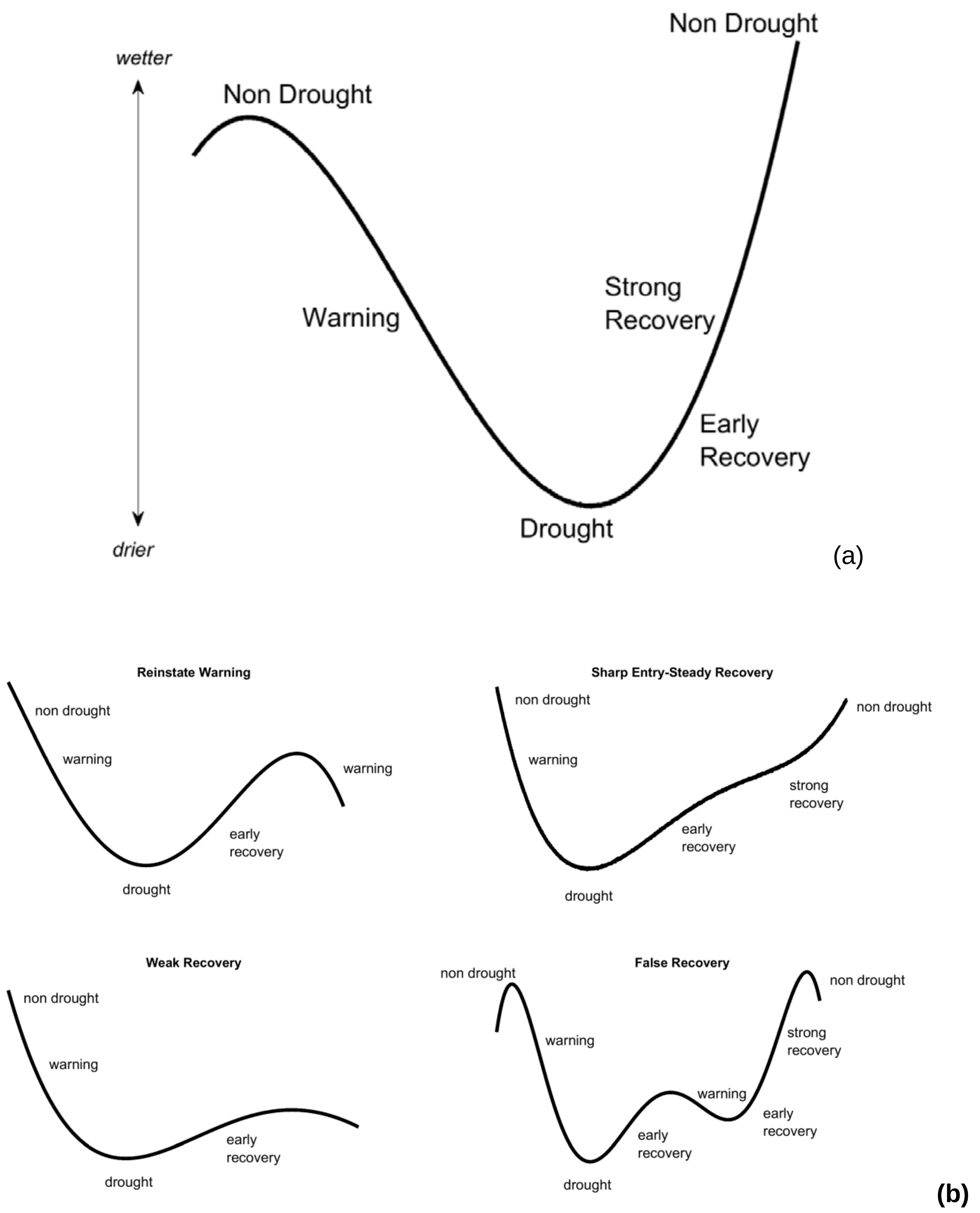


Figure 1. Conceptual version of the CDI framework; (a) illustrating drought phases using a theoretical sequence of climate variability; and (b) how the conceptual phases of drought can be applied to some real sequences of climate variability that have occurred near Dubbo on the central-western plains of NSW between 1915-2015. The sequences of (b) are constructed by fitting a 4th order polynomial to monthly soil water model output at this location and time is not to scale.

Materials and Methods

Enhanced Drought Information System

The conceptual CDI described in Figure 1 is embedded in a monitoring and information flow known as the Enhanced Drought Information System (EDIS). Figure 2 is a schematic of this system showing its main components. These are described in more detail below, starting from the left with the operational implementation of the CDI, and finishing to the right with a description of the primary data.

EDIS is a fully automated analytics and information flow that sources and then integrates climate (station observations) and remote sensing data, storing this information in a repository on a high performance computing environment. Integration is achieved in two steps, firstly by an agricultural modelling and data assimilation scheme (DPI AgriMod), and secondly, through a series of custom-built algorithms that calculate individual drought indicators that are then integrated by the CDI. Data from the CDI is passed to a web service, (which is not described in this paper) providing public access to this information as maps, time series and summaries. EDIS output is available from 1915 to present and is updated every day, providing a near real-time diagnosis of drought at two days prior to the current date.

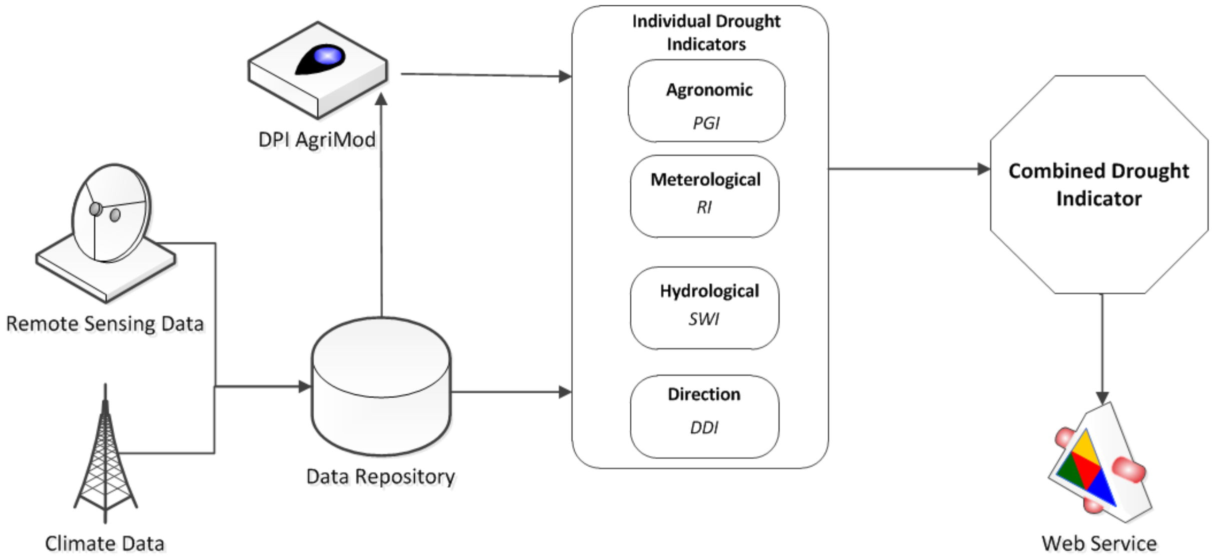


Figure 2. Technical schematic of the Enhanced Drought Information System used to calculate the Combined Drought Indicator. RI=Rainfall Indicator; SWI=Soil Water Indicator; PGI=Plant Growth Indicator; DDI=Drought Direction Index.

EDIS's algorithms have been custom engineered to perform computationally expensive tasks as efficiently as possible. Operational runs of EDIS need to be completed each day in a reliable and timely manner, with available time for processing around 30-60 minutes. The objective tests of the CDI described later in this paper involved repeated daily runs of EDIS given different configurations of the framework across 30-100 year climate periods. EDIS's algorithms were developed in MATLAB™, and compiled into C^{++} modules to run on a LINUX computing system. Automated data acquisition, quality control and deployment processes have been developed with shell scripts, tools like ASPERRA™ and File Transfer Protocol (ftp).

Combined Drought Indicator

In the conceptual CDI (Figure 1), 'Droughts' are periods of time when a rainfall deficit is driving a downturn in agriculture—relative to long term variability experienced in a given region—to a state where very little or no production is occurring. 'Non Drought' conditions are those times when lack of rainfall is clearly not adversely impacting on production. Regions may be experiencing adversely wet conditions or floods, that can impact on agricultural production in the period defined as 'Non Drought', so it is not an entirely accurate term. Early prototypes of the CDI used alternative terms, like 'preparedness' or 'normal', to describe this phase but 'Non Drought' was adopted after wide stakeholder consultation.

A 'Warning' is issued where there is a detectable downward (drying) trend and conditions are starting to limit agricultural productivity. The two recovery phases occur when there is a detectable improving trend in seasonal conditions. 'Early Recovery' signifies that a meteorological event has lifted conditions outside the range of what is considered a drought. 'Strong Recovery' signifies that conditions have continued to improve and production is building toward more optimal ('Non Drought') levels.

An algorithm was developed to quantify the conceptual CDI using a combination of four different indicators, encompassing meteorological, hydrological and agronomic definitions of drought. The calculation of the individual indicators is described in more detail below.

Adopting the approach described by Svoboda et al. (2002) and Sepulcre et al. (2012), a CDI algorithm was developed as a series of decision rules, which hinge on key thresholds and indicator values to partition the status of condition into the different phases, (defined in Table 1). This configuration of the CDI algorithm was the outcome of trial and error testing and stakeholder consultation, which are encapsulated in the objective testing presented later in this paper. A key feature of the CDI is the use of an 'or' rule to combine the indicators to signify 'Drought'. This means that a land area is deemed to be in this phase irrespective of which historical indicator falls below the critical threshold used to define drought (10^{th} percentile in Table 1) or the other drought phases. Similarly a 'Warning' is issued when any (using the 'or' rule) of the three historical indicators falls below the 50^{th} percentile, under a drying trend signified by a negative Drought Direction Index.

The 'and' rule is applied to define 'Recovery' and 'Non Drought' phases in the CDI. For a region to transition out of a 'Drought' phase there must be strong evidence as all three historical indices need to satisfy the 'Recovery' and 'Non Drought' criteria for these phases to be declared. Thus the CDI has been configured to be more responsive during drought entry to provide early warning, and less responsive during drought exit so that conditions are carefully monitored during recovery.

The decision rules in the CDI algorithm have been configured in this way to address the uncertainties inherent in multiple and competing drought definitions transparently and consistently. A precautionary approach, where the weight of evidence falls toward ‘Drought’ declaration, is built into the framework. Using the ‘or’ rule to define ‘Drought’ and ‘Warning’ means that these phases will be triggered regardless of how drought is defined as long as one indicator satisfies the criterion. At a practical level this means that a ‘Drought’ will be recognised by the framework when rainfall has been ineffective for production, and conversely, a ‘Drought’ will be still be flagged when there is ‘green pick’, or a region is under so-called ‘green drought’ conditions.

Table 1. Decision rules used to produce the operational Combined Drought Indicator. Rules are applied in an algorithm which incrementally screens and classifies data into drought phases, using time series data for four drought indicators: RI=Rainfall Indicator; SWI=Soil Water Indicator; PGI=Plant Growth Indicator; DDI=Drought Direction Index. Rule symbols: less than (<); less than or equal too (<=); greater than (>); greater than or equal to (>=); equal to (=). Thresholds (T) are defined in the table.

Phase	General description	Decision rules
Drought	Long term rainfall and soil moisture deficit. Rainfall not effective for production. Plant production failed.	RI <= $T_{drought}$ or SWI <=$T_{drought}$ or PGI <= $T_{drought}$
Warning	Short precipitation deficit. Conditions beginning to change.	DDI = negative and RI < T_{normal} or SWI <T_{normal} or PGI < T_{normal}
Early Recovery	Rainfall has occurred over a single season. Soil moisture has increased. There is a chance of re-entering drought.	DDI = positive and RI > $T_{drought}$ and <$T_{recovery}$ and SWI >$T_{drought}$ and <$T_{recovery}$ and PGI > $T_{drought}$ and <$T_{recovery}$
Strong Recovery	Falls of rain have occurred over a production cycle, soil moisture is available and production is underway but not yet realised in economic yields.	DDI positive and RI > $T_{recovery}$ and <T_{normal} and SWI > $T_{recovery}$ and <T_{normal} and PGI > $T_{recovery}$ and <T_{normal}
Non Drought	Rainfall deficits are not limiting production. Economic yields have been achieved in one season, and prospects are good for the coming season.	RI >= T_{normal} and SWI >= T_{normal} and PGI >= T_{normal}

Thresholds

$T_{drought}$= indicator value below which drought occurs. 10th percentile.

$T_{recovery}$= indicator value defining early and strong recovery. 30th percentile.

T_{normal}=indicator value above which normal conditions occur. 50th percentile.

The choice of historical thresholds is an important technical decision in the formulation of a drought monitoring system, and expert interpretation is often used to justify choice. In the Australian literature describing drought monitoring, various thresholds have been used as the critical threshold value which define a drought. Typically this is set below the 20th percentile, with the 10th and 5th percentile being common choices (for reference to examples see the special issue by White et al. 1998). Beyond the past use of these thresholds in Australian drought monitoring there is limited guidance concerning the choice of thresholds for drought events, and even less guidance around the use of thresholds to define entry and recovery. As described below, this feature of the CDI is explored thoroughly with objective testing, building justification for choice of the 10th percentile in Table 1.

Spatial aggregation

For public reporting, the CDI and individual indices are aggregated from the calculation scale ($5km^2$ grid cells) to a parish level. These scales of aggregation are illustrated with an example in Figure 3, highlighting parishes in relation to the underlying $5km^2$ grid. NSW parishes provide a convenient reporting unit for a spatial process like drought, as they are fine enough to capture the spatial variability associated with major drought events across the State, but make it difficult to identify individual farms. This is an important requirement under privacy considerations for NSW Government where individual farm level information is not publicly disclosed. It is also a way to reflect the geographic precision of the underlying gridded climate data sets in EDIS. There are 7378 parishes in NSW with the larger parishes located to the west of the State reflecting sparser settlement patterns. Generally NSW parishes contain 4-5 $5km^2$ grid cells, which for most of the State would contain 10-20 individual property holdings. The largest parish in the west of the State has 27 grid cells, while there are 300 parishes in the eastern Sydney metropolitan and urbanised coastal (non-agricultural) regions that only have 1 grid cell.

The aggregation algorithm finds the relevant centroids of the underlying grid, with a $4km^2$ buffer around the parish boundary to account for uncertainty in the underlying gridded data. This is shown in the example for Athol in Figure 3. The average of the gridded data is calculated for the individual indicators, while the mode is taken for the CDI because it is categorical.

While the aggregation to parish level accounts for privacy requirements and some of the uncertainties in the climate data, it also provides a systematic and repeatable approach to one of the elements of criticism leveled at broader scale drought monitoring in Australia (Keogh 2015; Botterill 2013). It provides a consistent and repeatable procedure to establish boundaries for operational monitoring, rather than relying on analysts or decision makers to interpret regularised grids to establish administrative boundaries, which introduces a subjective decision. Importantly, reconciling regional environmental data with on-farm conditions is a multifaceted problem, encompassing not just the subjectivity of establishing boundaries, but extending to technical factors like modelling (interpolation) methodologies and the density of observation networks. Issues around error and uncertainty in local climate representation have not been addressed in the development of EDIS and the CDI to date.

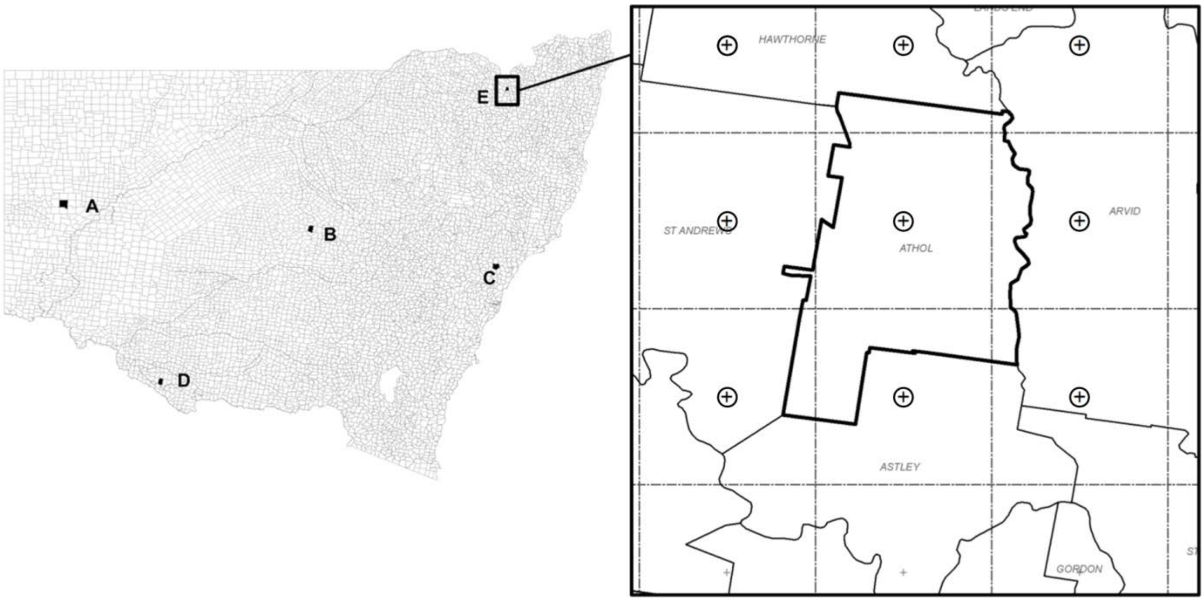


Figure 3. Classification of the CDI to NSW Parish level for reporting and web service. NSW Parish Boundaries (left), with an example for Athol in Northern NSW (right). AWAP grid boundaries are hashed lines. Crosses are AWAP (5km^2) centroids, with circled bold crosses indicating the grids selected by the aggregation algorithm for the Athol Parish. Illustration Parishes: A=Burnayto, B= Beaconsfield, C=Hay, D=Toolon, E=Athol.

Individual drought indicators

Percentile-based indices have been used to construct the three historical indicators of drought that form the CDI, i.e. the Rainfall Index, Soil Water Index and Plant Growth Index. These have been chosen from a wide range of approaches that have and are continually being developed by the global drought monitoring community (for overviews see Clark and Mullan 2011; White and Walcott 2009; Sivakumar et al. 2014).

Percentile-based indices are the most common method used for calculating drought indicators in Australia, and involve ranking a period of interest relative to those experienced in the past (Gibbs and Maher 1967; White et al. 1997; Mpeloska et al. 2007). Percentiles provide a way of normalising for variability in a given climatic environment with few assumptions or need for calibration. It is different to the Standardized Precipitation Index (SPI, McKee et al. 1993) or the Palmer Drought Severity Index (PSDI, Palmer 1965 with modern updates by Wells et al. 2004) which are the common indices used in international applications. Indices like the SPI and PSDI require the definition of a series of physical assumptions either a-priori or by calibration. Percentile-based indices provide an approach with fewer assumptions, have been well tested in Australian conditions (Gibbs and Maher 1967; White 1998) and are widely understood by stakeholders in Australia.

In EDIS, an optimal method of tied-ranks (Krauth 1971) is used to establish an ordered range of past conditions in which a period of interest is ranked for a given base period (30 years 1985-2015). Once an entire time series has been percentile ranked the data have a uniform distribution regardless of their climatic setting. This is an attractive feature in NSW given the presence of semi-arid rangeland, temperate and sub-tropical climates, which have left-skewed and log-normal daily rainfall distributions. Under Australian conditions, particularly those found in the rangelands and semi-arid zone, indicator methodologies that do not apply a strong transformation result in discontinuity and instability, and require region-by-region interpretation.

Meteorological Indicator

The Rainfall Index (RI) is the percentile rank of daily rainfall data summed over a 12 month summation period. From herein the summation period is termed the ‘aggregation window’. On a given day, the previous 12 months’ (365 days) data are aggregated then ranked within the baseline range obtained from 1985-2015. This is repeated for every day from 1915 to build an historical data base of 100 years. The RI is an index between 0 and 100, where, for any given climatic environment, values approaching 0 are close to the driest on the historical record and those approaching 100 are close to the wettest.

Hydrological Indicator

The Soil Water Index (SWI) is calculated using the same procedure as the RI, but uses a soil moisture field derived from the DPI Agri-Mod soil water balance. Here the plant available soil water from layer 1 (0-10cm) and layer two (11-45 cm) are aggregated and used. In most districts of NSW, a SWI value between 0 and 10 means that there is no plant available water held in the profile. The SWI is a hydrological index, but its configuration means that it is more useful as an indicator of conditions for dry land agriculture.

Agronomic Indicator

The Plant Growth Index (PGI) is also calculated using the same procedure as the RI, but uses the output from the DPI Agri-Mod crop and pasture models. Both the crop stress and pasture growth fields are taken from DPI Agri-Mod and the percentile rank calculated for each day. If the predominant land use in a given area is cropping, according to the National Dynamic Land Cover Dataset (see Table 2), the PGI uses the crop model output. Otherwise it is calculated using the pasture model output. The PGI is an agronomic drought indicator which is not only sensitive to soil moisture but also temperature variation, including events like frosts, as well as the radiation budget.

The PGI tracks the climatic limits for production at a broad geographic scale (a 5 km^2 grid). It is an indicator of the likelihood of climate limiting farm primary production and not a metric of actual production. Farm level management factors, for example fertilisation programs, crop rotations and stocking tactics interact with climate to influence in field production levels. While it is possible to track the average climate signal comprehensively at a regional scale across the State, it is not feasible to accurately track the configuration and effects of management in every farm and paddock. High levels of accuracy and precision at the paddock level are also not required for Government drought monitoring, where indicators at a regional scale are sufficient to guide drought declaration and targeting of community support.

Drought Direction Index

A Drought Direction Index was constructed to provide information about trends in seasonal climate for the ‘Warning’ and ‘Recovery’ phases of the CDI. It was developed because early trial and error tests of the CDI highlighted that when using the threshold indices alone it was not able to reliably distinguish the ‘Warning’ from the two ‘Recovery’ phases.

For each day in the RI a robust linear regression, which is not overtly sensitive to outliers, is fitted to the previous 90-days, and the slope of this function retained to form the DDI. The value is rescaled to a range between -60 and +60 to visualise the index. The key information is not the magnitude of the DDI across this scale, but the sign of the index. If the value is negative there is a drying trend, and if it is positive the area is getting wetter. The Drought

Direction Index is used as a categorical index only, because skill testing not reproduced in this paper, established that it has limited predictive or forecasting value.

DPI Agri-mod

The modelling platform in EDIS is called 'DPI Agri-Mod', and it is described at a technical level in Appendix 1. It is a coupled water balance, pasture and crop modelling framework that can be run in near real time with assimilation of daily climate and 14 day composite feeds of remote sensing data. The long term tests of the CDI reported in this paper have the assimilation procedure turned off as the remote sensing time series begins in 1970. The model architecture is an integration of: a three layer fore-restore water balance which is structurally similar to the approach described by Rickert et al. (1998), a simplified biogeochemical growth model where the Gross Primary Productivity (GPP) equation of Kirschbuam (2015) has been modified for grasses and the radiation use efficiency parameters are modified by remotely sensed NDVI; and a temperature-radiation crop development function (based on Li et al. 2012 and APSIM 2015). A sophisticated model optimisation procedure (described in Appendix 1) was developed to calibrate the system using a second source of remote sensing data, where GPP is derived from MODIS 250m resolution data (Donohue et al. 2014). The optimisation provides state-wide estimates of the models parameters on the 5km^2 grid.

Data

The data sets used to develop and run EDIS are described in Table 2 where they are divided into 4 main classes: climate, remote sensing, soil and field data. These serve as a development and/or operational purpose. Operational data provides information about conditions in near real time and are used to actively run the system each day. Developmental data sets are used for various purposes including model parameterisation and verification, as well as information used when upscaling and downscaling. Most data, excluding the field data sets, are publicly available under the Australian Research Data Commons.

Table 2. Climate, soils, remote sensing and field data used to operate and develop the Enhanced Drought Information System. BoM, Bureau of Meteorology; TERN, Terrestrial Environmental Research Network; ABS Australian Bureau of Statistics; uSyd, University of Sydney; uMel, University of Melbourne; uNew; University of Newcastle; ANU Australian National University

Class	Item	Source	Use	Properties
Climate	Australian Water Availability Program (Rainfall, Max/Min Temperature, Radiation, Potential Evaporation)	BoM	Development Operational	Gridded, $5km^2$ resolution, daily
	ANU Climate	TERN/ANU	Developmental	Gridded, $1km^2$ resolution, daily
Remote Sensing	MODIS and derived products Fraction of photosynthetically absorbed Radiation (fPAR) (1km) Leaf area index (LAI) (1km) National Dynamic Land Cover Dataset (250m) Actual Evaporation (250m) Vegetation Indices (250m, 500m) Gross Primary Production (250m)	CSIRO/ TERN/ GeoScience Australia	Development	Gridded, various resolutions, dekads and months
	AHVRR Normalised Difference Vegetation Index (NDVI) (1km)	BoM	Development /operational	Gridded $1km^2$ Dekads
Soils	Australian Soil Landscape Grid	CSIRO/ uSyd/TERN	Development	Gridded, 90 meter
Field data	Crops - Wide range of research data sets	NSW DPI	Development	Point time series and aggegated (ABS) statistics
	Pastures - Wide range of research data sets	NSW DPI	Development	Point time series Observatons over regions
	Soil moisture Key sites data, OZFLUX Murrumbidgee experiment, Nth NSW experiment	NSW DPI/uMel/ uNew	Development	Point time series

Climate

The Australian Bureau of Meteorology (BoM) is a key source of data as it operates an extensive network of climate stations (Figure 4). Meteorological data collected at these stations is upload to the BoM's centralised database by various pathways, where it is then quality controlled. As shown in Figure 4, a number of stations are 'automatic', and data is uploaded on a sub-daily or daily basis by telemetry. Other stations are 'open' but there are lags between collection time and upload, and it may take days out to weeks. Other stations are 'closed' and not actively monitoring current conditions, but the data is used to construct the long term historical record. Although there is reasonable coverage across NSW for all three station types, it is higher in the more populated areas to the east coast of NSW, grading to lower station densities in the far west. At the time of publication the BoM in partnership with the NSW Government is actively increasing the density of weather stations in the NSW agricultural zone, principally in western regions.

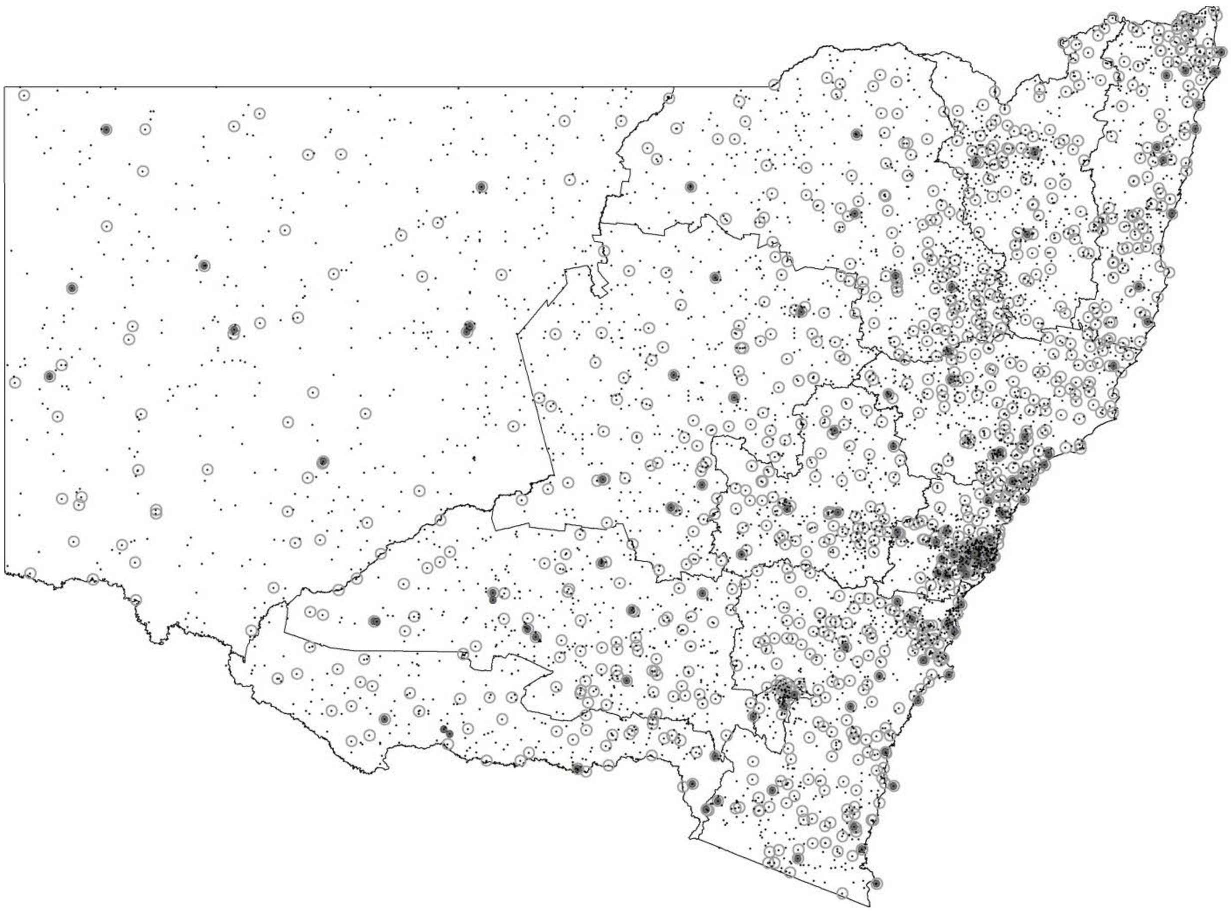


Figure 4. Climate station network in NSW reporting daily rainfall in 2016: Automatic stations (dot with dark filled circle); Open stations (dot with open circles); Closed stations (dots only). Regions are Local Land Services areas.

Daily station climate data is extracted from the BoM's national database and interpolated to produce climate fields on a continuous regularized grid with a specified resolution. At present this is completed by the BoM who provide the operational gridded data from the Australian Water Availability Program (AWAP, Raupach et al. 2008), which is daily climate data on a 5km^2 grid. The interpolation for AWAP (Jones et al. 2009) is carried out with ANUSPLIN (Hutchinson 1984; Hutchinson 1991a; Hutchinson 1991b) which is used widely in Australia (Jones et al. 2009; Jeffries et al. 2001) and internationally (Tait et al 2006; Haylock et al. 2008; Hutchinson et al. 2009). Jones et al. (2009) undertook a through error analysis of this data set, where in summary daily temperature models for New South Wales had standard errors between 1.0-2.5 $^\circ$C (approximately 1-10 percent of the range) and daily rainfall models had errors of 1-20mm (approximately 5-200 percent of the range).

The full historical record (only 1915 onward for the full suite of variables) is stored in the EDIS data repository, with updates (2 days prior to the current date) transferred from the BoM each day. EDIS uses daily rainfall (mm/day), maximum and minimum temperature ($^\circ$C), solar radiation (mj/m^2/day) and potential evaporation (mm/day). ANUSPLIN is implemented using topography (height above sea level) as a co-variate thereby improving the interpolation scheme (Jones et al. 2009), while radiation also uses remote sensing as a covariate (Grant et al. 2008). Potential evapotranspiration is calculated by the BoM using Moreton's bare water method (Moreton 1986). In the future EDIS will run on data from an alternative interpolation scheme called ANUClimate (Hutchinson *pers com* 2016) where improvements have been made to the implementation of ANUSPLIN, with error reductions in temperature and rainfall schemes, and 1km^2 resolution data is produced.

Vegetative remote sensing

In addition to the remote sensing used in the interpolation of station radiation observations, EDIS uses vegetative remote sensing to track the condition and locality of crops and pastures (Table 2). The use of remote sensing is critical in drought monitoring (McVicar and Jupp 1998) as it provides additional and spatially richer information to the meteorological network. This is particularly important in regions where meteorological station density is low, such as Western NSW.

This data is used for a number of purposes in the development of EDIS as well as part of the operational near real time monitoring. Key data and its uses include: landuse and vegetation locality data derived from MODIS (250m^2) to constrain and partition crop and pasture models (the National Dynamic Land Cover Dataset, Lymburner et al. 2010); remotely sensed gross primary production (GPP) data (250m^2 MODIS, Donohue et al. 2014) in model development; assimilation of 1km^2 Advanced Very High Resolution Radiometer (AVHRR) NDVI into the underlying crop and pasture models. The Dynamic Land Cover Dataset and the GPP data were sourced through the Terrestrial Environmental Research Network under the Australian Data Commons license, while the AVHRR data feed is provided by the BoM.

Integration of remote sensing data into the system is challenging, as it is in different spatial and temporal scales to the daily meteorological data feeds and there are often significant quality issues and missing data. Aggregation to the effective monitoring scale ($5km^2$) was achieved firstly by filtering out non-agricultural vegetation, and then by selecting the predominant value of the Dynamic Land Cover Dataset within the $1km^2$ AVHRR grid. Pixels defined as crop were selected and aggregated to provide the cropping signal at the $5km^2$ grid scale, and this procedure was repeated for pastures. This provides a way of filtering the crop and pasture signals from those where the predominant land cover is trees or woody shrubs.

Soils

Data quantifying the gravimetric available water capacity (AWC, %) across the NSW landscape were sourced from the Soil Landscape Grid of Australia (SLGA, Grundy et al. 2015). Data was collated for depth increments of 0-5cm, 5-15cm, 30-60cm, 60-100cm, 100-200cm, on a 90 by 90m grid. The Soil Landscape Grid of Australia is a sophisticated digital soil mapping model (Viscarra Rossel et al. 2015a; 2015b). Aggregation of this data and its use in the crop and pasture models is similar to the technique described for the remote sensing data. The 90m scale soil fields were classified to reflect the predominant Dynamic Land Cover Dataset value. Non-agricultural land use was removed and the remaining soil field values were aggregated to the $5km^2$ grid scale by taking the average, highest and lowest. These values are not used to parameterise the soil water balance in DPI Agri-Mod directly, but alternatively, provide the starting point and a set of boundary conditions in the model optimisation procedure (Appendix 1).

Field data

Field and survey data sets have been collated as part of on an ongoing strategy by the NSW Department of Primary Industries to build a network of measurement and ground observations. Site specific data was available for 37 pasture (growth and biomass) and 12 crop experiments (yield and biomass). This data was supplemented with hydrological experimental data sets where soil moisture probes had been installed, including both neutron and electromagnetic derived soil water measurements. Broader area data describing seasonal pasture response were available from the PROGRAZE program. Comprehensive survey data was available for annual crop yield averaged across large areas within the dryland cropping zone (NSW Agronomy Zones and Local Government Areas). This data has been used to provide an independent validation of the soil water, crop and pasture modules (see Appendix 1 for further information).

Stakeholder engagement

Engaging stakeholders during the development process is the most effective way of breaking down ‘operational indeterminacy’, the well-known situation of poor alignment between the technical aspects and stakeholder requirements of a drought monitoring system (Steinemann and Cavalcanti 2006; Sivakumar et al. 2014). A stakeholder map has been developed to describe the range of stakeholders and their needs and requirements in NSW (Figure 5). The stakeholder groups for the CDI are diverse and have different and sometimes competing objectives. There are multiple institutions in NSW Government from Ministers through to Departments and branches within departments; a similar range of Government institutions from the Commonwealth and other States in Australia; industry organisations; agri-representation organisations; rural communities; and individual farmers. Other research organisations who directly contribute data to EDIS are also stakeholders, as well as agencies with an interest in drought monitoring.

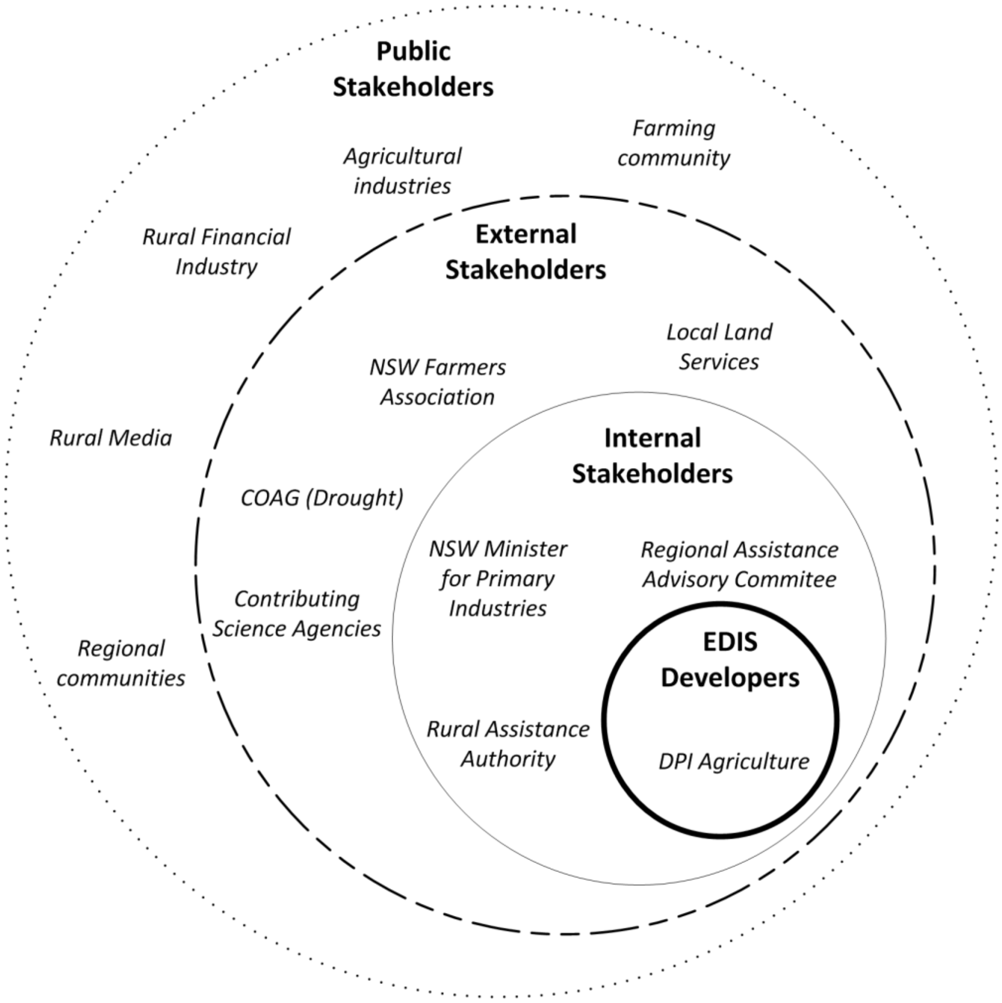


Figure 5. A generalised stakeholder map for the Enhanced Drought Information System.

While this paper describes the final form of EDIS and the CDI, their development followed a highly iterative process with targeted stakeholder engagement. The initial focus was on engaging direct users of the framework or the internal stakeholder group towards the centre of Figure 5 to examine a number of conceptual prototypes. This was followed by a period of technical development where EDIS was built and a number of working prototypes of the CDI constructed. This was achieved by establishment of an internal Steering Group as well as external Technical Reference Group with representatives from the internal and external stakeholder groups in Figure 5. A formal deliberative workshop was also undertaken to engage regional experts, drawing knowledge and experience from the external and public stakeholder groups. This focussed on testing the management efficacy of the framework, and followed by another period of technical development. As the engagement process evolved its focus shifted from the technical properties of the system (the development and internal stakeholder group in Figure 5) toward language and imbedding the active decision making processes (the external and public stakeholder groups in Figure 5).

The deliberative workshop was an important juncture in this process and the outcomes led to the configuration of the conceptual framework presented in Figure 1, as well as yielding information about the management efficacy of the framework. Six rural professionals were selected from different regions to provide a degree of state wide representation. They are a key point of contact in the community-Government relationships that needs to be built to administer drought support. These experts have direct interaction with rural communities and farmer stakeholder groups, and are also fully engaged with Government and industry. In the workshop the experts were actively engaged by charging them with: critiquing prototypes of the CDI including the terminology to describe drought phases; developing their own multi-indicator framework; and finally actively linking their preferred framework to management actions they would take as professionals and also as farmers.

Establishing widely accepted terminology to describe the phases of the CDI proved to be a difficult objective, as there were divergent views between technical, user and Government stakeholders. An example is the process that ultimately led to using the term ‘Non drought’, where the term ‘preparedness’ was originally proposed by the EDIS development team. The user stakeholder group rejected this term in the deliberative workshop, and after considering alternatives like ‘no drought’, ‘inter-drought’ and others, settled on the term ‘normal’. The term ‘normal’ was subsequently not supported by scientific experts who were members of the project’s Technical Review Group who identified that this was inaccurate and potentially misleading for risk management. Similar debates occurred about the use of ‘Warning’ as opposed to ‘Drought Watch’. The final terminology in this paper is a compromise, but strong divergent views remain and are likely to exist across stakeholder groups.

Objective testing

The performance of a drought monitoring systems should be thoroughly understood before it becomes operational (Sivakumar et al. 2014). A series of tests have been designed to track how the CDI performs, providing information for the stakeholder engagement process. The final configuration of the CDI and individual drought indicators described above is based on the tests and engagement outcomes. The main outcomes and insights into the performance of the CDI are reproduced in the results section of this paper.

Consistent with development of drought monitoring systems worldwide, initial ‘trial and error’ tests were undertaken to examine low level data quality and how the algorithms functioned. Here exploratory analysis techniques were used by analysts to assess the progression of the CDI over time across NSW. Animation proved a useful technique to explore how the CDI tracks the complex spatial and temporal process of drought formation and recession. This has been reproduced in this paper as a series of maps and time series. Some additional work was undertaken to examine the relationships between individual drought indicators and explore the rationale for combining rather than using individual indices.

The first formal objective test examines the sensitivity of the CDI to the configuration of the individual indicators. Here the CDI was re-calculated using indices configured with aggregation windows of 6, 12, 18 and 24 months, with corresponding historical threshold values of 5, 10 and 15 percent. From this data the proportional change (sensitivity) in the time spent in drought to a single unit changes were calculated. That is, calculation of the change in drought probability for a 1-month change in the aggregation window, or a 1-percentile change in the historical thresholds.

The second objective test examined the sensitivity of the CDI to changes in the base period used to calculate the historical thresholds. Firstly the CDI is re-calculated by lengthening the base period incrementally by 10 year segments, starting with the period 1985-2015. Then the CDI is calculated by moving a 30 year base period through the period 1920-2010. This is supplemented by time series analysis that tracks the probability of drought occurrence across NSW in 10,20 and 30 year windows. These tests provide some insight into the effects of a changing climate on the CDI, and particularly the validity of using historical drought indices under non-stationary conditions.

Finally the probability of transitioning from a ‘Warning’ phase into a ‘Drought’ is calculated for a one month and three month (seasonal) time frame. This is achieved by iteratively screening the data, and if the CDI is in a ‘Warning’ phase recording if a drought occurs at any time in the next one or three month periods.

Results

Combined Drought Indicator

The output of a full 100 year run of EDIS is a categorical data set of the CDI for each day on the 5km^2 grid (1.84e^{+09} observations) across NSW, which is then aggregated to the parish level for reporting. This daily sequence of parish level output was animated and viewed to evaluate the CDI framework for discontinuity and stability. Figures 6 and 7 illustrate the animation using a truncated time sequence of the CDI. Figure 6 are maps of the CDI for mid-January every 5 years from 1920-2015. Figure 7 are the mid-month value of the CDI for the period encompassing the Millennium Drought (2001-2010).

These spatial sequences illustrate the observations made when viewing the animated time series that the multi-indicator calculation procedure and aggregation algorithm underpinning the CDI builds, as a continuous spatial classification of drought states. The boundaries are smooth, and there are no detectable discontinuities as the sequence of maps evolves through time, and drought events are tracked as continuous spatial units. These properties establish that, at a fundamental level, the decision rule approach to combing drought indicators and the aggregation to parish level provides a stable calculation for use in climate monitoring and analysis.

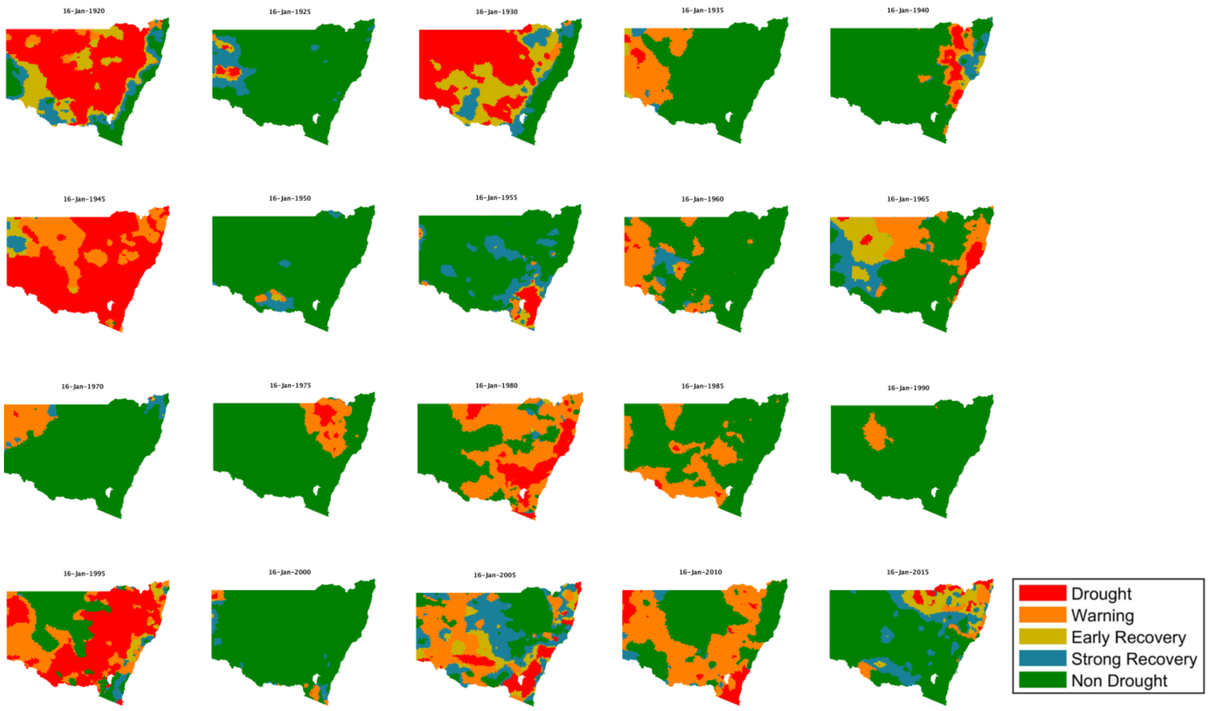


Figure 6. The CDI on January 1 every 5th year for the period 1920-2015. This truncated series illustrates the spatial structure of the CDI observed when the complete record is animated.

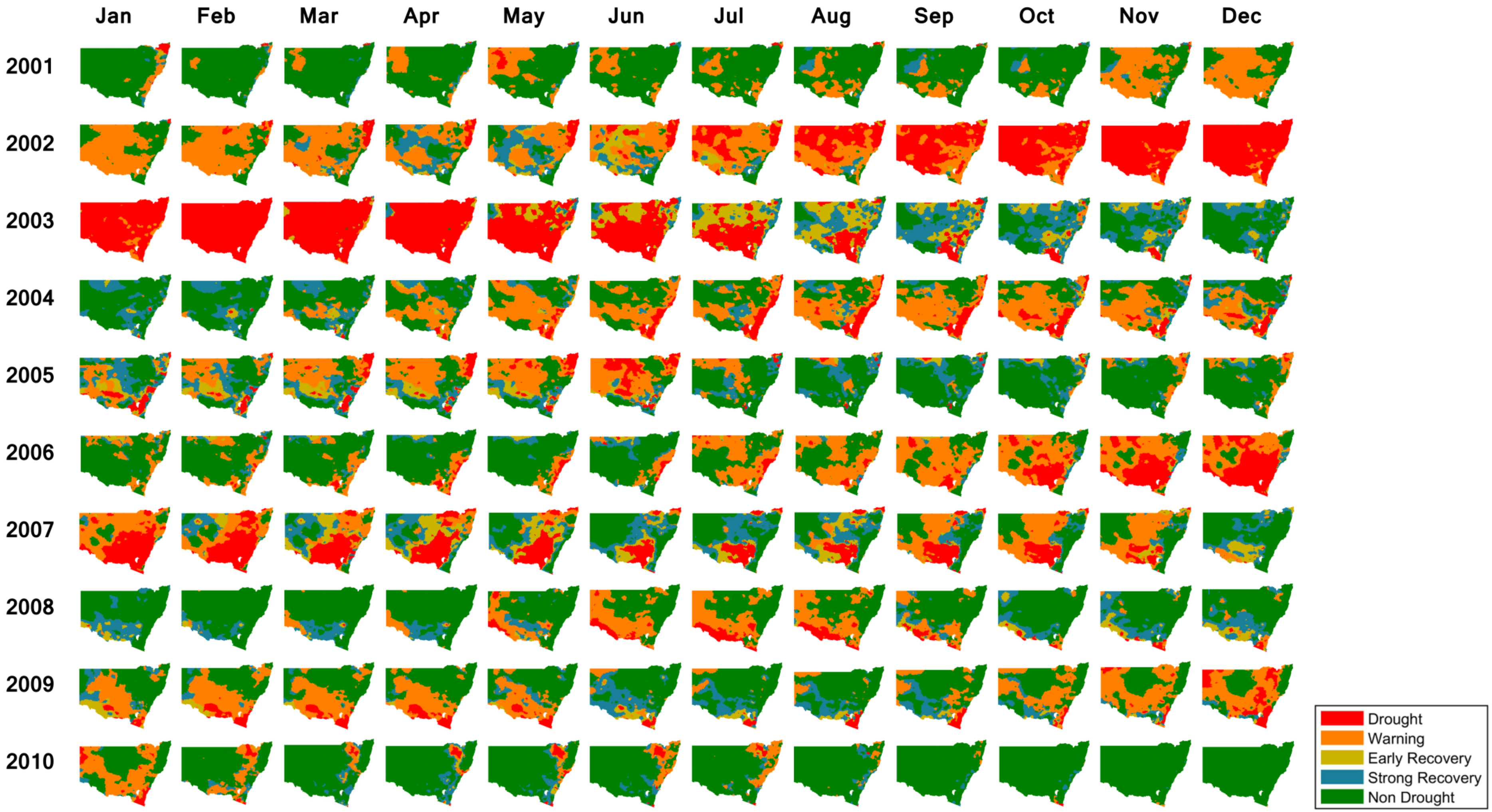


Figure 7. Mid-month values (day 16) for the CDI for the period 2001-2010.

Another way to explore the behavior of the CDI is to examine the percentage area of NSW in each drought phase over time. A stacked area plot is provided in Figure 8 focusing on the period 1960-2015, while the full sequence (1915-2015) is provided in Appendix 2. This plot reveals rich information about the properties of drought at an aggregate level, for instance the well-known 'partial randomness' of drought events, where widespread events seem to occur approximately every 10-20 years, but with no repeatable pattern or regular frequency (Gordon 1993). Close examination highlights that each drought event has its own unique sequence of entry, progression and recovery. For example the 1982 drought progressed quickly across NSW with many parishes transitioning rapidly from a 'Warning' to a 'Drought' phase in the CDI sequence. Whereas there was a prolonged slow entry into the 2002 drought event where much of the state was under a 'Warning' phase for up to 6 months before the area under 'Drought' increased markedly in January-March 2002.

The area-time sequence plot in Figure 8 also highlights that there is usually a rapid transition from 'Drought' through the 'Early Recovery' and 'Strong Recovery' into a 'Non Drought' phase, and it is also possible to transition from the recovery phases back to 'Warning'. This re-enforces the application of the conceptual model in Figure 1(a) to the realistic sequences in Figure 1(b) where descriptive terminology like 'false recovery' and 'weak recovery' and 'sharp entry' are used to describe the variability. The CDI data in Figures 6-8 provide some analytical evidence that using this nomenclature to describe drought has an objective basis.

The nature of the transition between CDI phases is illustrated in more detail for three individual parishes in Figure 9 (locations shown in Figure 3). This shows the sequence of the CDI and corresponding values for the individual indicators as time series from 2000-2010 in A (Burnayto), B (Beaconsfield) and C (Hay). The extended 1915-2015 time series is also provided in Appendix 2.

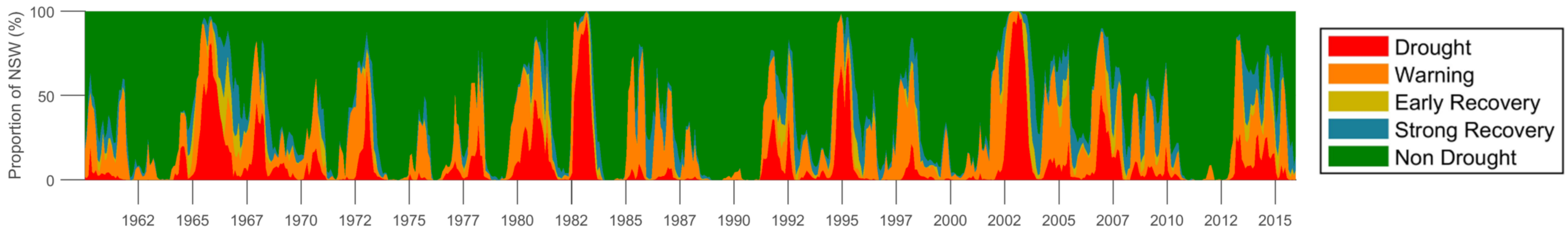
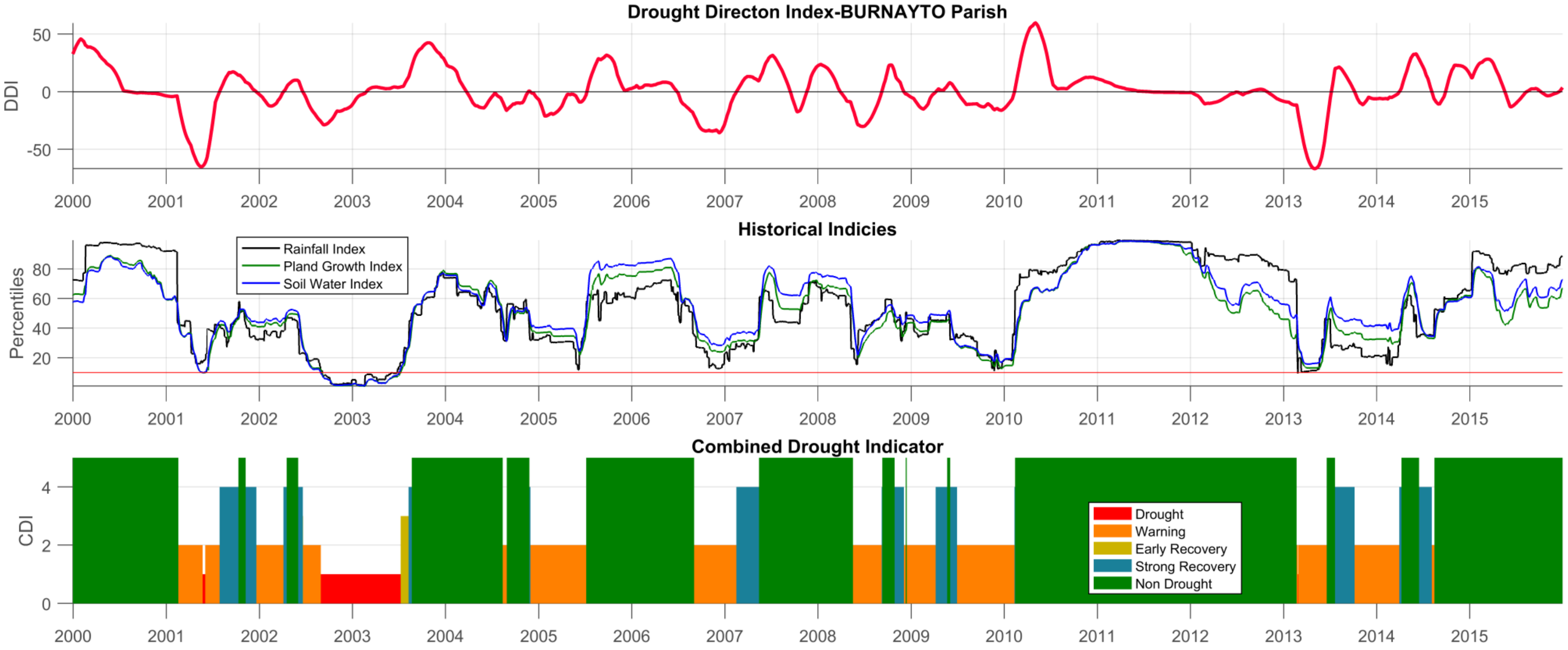


Figure 8. Proportion of NSW (%) in each CDI phase 1960-2015. The series from 1915-2015 is in Appendix 2.


Drought Directon Index-BURNAYTO Parish
DDI
50
0
-50
2000
2001
2002
2003
2004
2005
2006
2007
2008
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2012
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2015
Historical Indicies
Percentiles
80
60
40
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Rainfall Index
Pland Growth Index
Soil Water Index
Combined Drought Indicator
CDI
4
2
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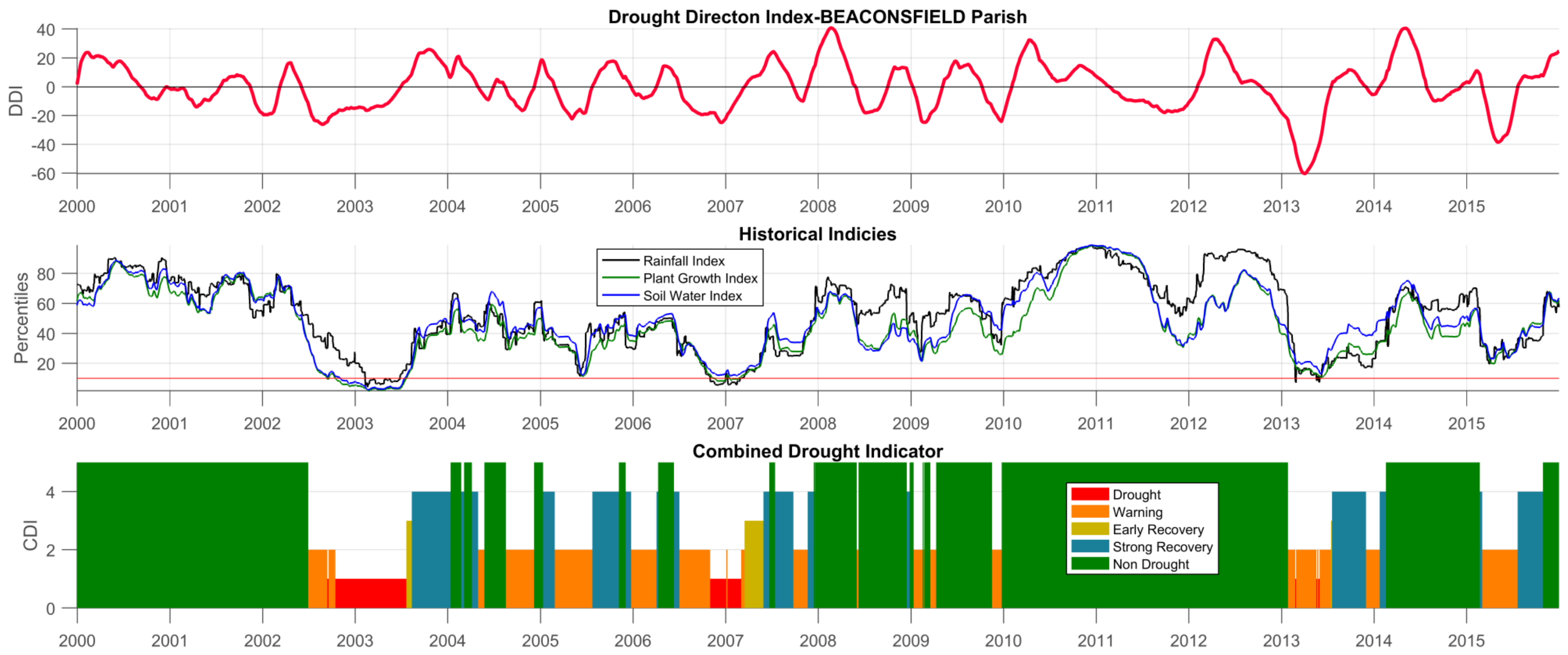
Drought
Warning
Early Recovery
Strong Recovery
Non Drought


Drought Directon Index-BEACONSFIELD Parish
DDI
40
20
0
-20
-40
-60
2000
2001
2002
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2011
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Historical Indicies
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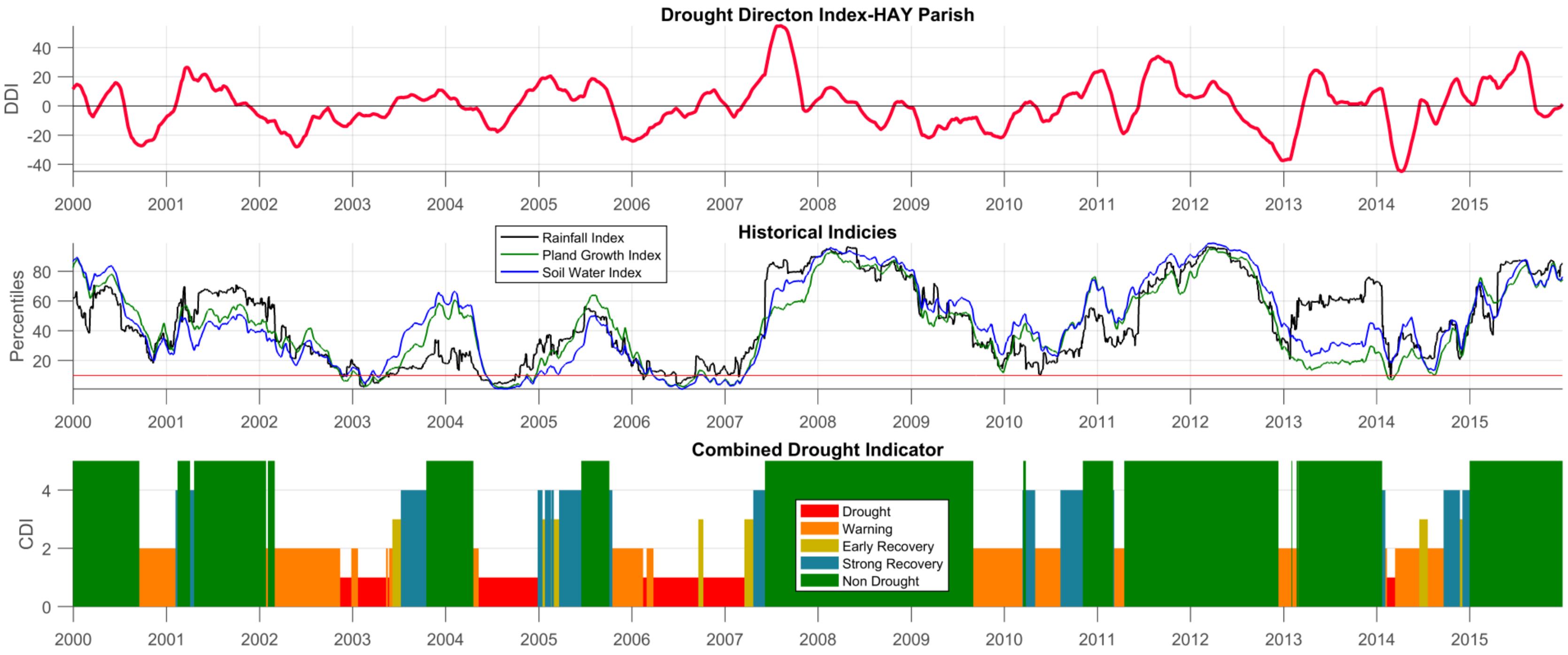

Figure 9. Time series of the CDI and individual drought indicators from 1960-2015 for A: Burnyato, B:Beaconsfield, C: Hay. The series for 1915-2015 is in Appendix 2.

Focusing on the CDI time series at the bottom of the individual parish time series (Figure 9), the exit from the 2002-03 drought event followed the sequence expected by the conceptual model of the CDI (Figure 1a) with a period in 'Weak Recovery' followed by some months in 'Strong Recovery' before transition into 'Non Drought'. However, other periods in this series do not follow this pattern. For example the exit from the 2005 drought event in the Hay parish was characterised by a series of weak recoveries, with transition from 'Early Recovery' to 'Strong Recovery' and back again over 6 months. There are also examples in this time series where the CDI transitions from 'Non Drought' back into 'Strong Recovery' (for instance during 2006 in the Beaconsfield parish). Here the DDI remains positive but soil moisture has dried sufficiently through evapotranspiration for the SWI to fall below the 50th percentile threshold. Similarly the CDI is 'Non Drought' for much of 2013 and 2014 in the Hay parish, with a slightly positive DDI and the RI tracking around the 50th percentile, yet the SWI is at approximately 30 and the SWI lower at the 20th percentile. While the CDI provides a simple management orientated diagnosis of drought, this points to the subtle behavior, and complex relationships, in the individual drought indicators and their interplay in the CDI algorithm.

Historical indicators

The time series of the RI are shown in the historical indices graph in Figure 9 (1960-2015) and the extended series in Appendix 2 (1915-2015). For reference, the 10th percentile identifying the drought threshold is shown as a red line. Figure 9 illustrates that configuring the RI with a 12 month averaging window provides a drought indicator that is not overly sensitive to individual months of high or low rain, yet it is sensitive to sustained periods of low rainfall of approximately 3-6 months in duration. For example it is not overtly sensitive to single rainfall events, like a wet month, but it takes sustained rainfall over a period of 1-2 months for the RI to change from 'Drought' levels (below the 10th percentile) and reach normal (above the 50th percentile) conditions. The RI has a degree of localized noises, small fluctuations up and down over days and weeks, reflecting the episodic nature of individual rainfall events recorded as daily aggregates.

Spatial fields of the RI are provided for a short sequence of time in Figure 10 (February, June and October 2000-2005). Like the general analysis of the CDI described previously, these illustrate a continual animation that was viewed to examine the spatial patterns in the whole daily time series from 1915-2015. Similar to the CDI, the spatial fields of the RI appear to be continuous spatial units with no detectable discontinuities, in other words there are smooth changes to the spatial pattern to the RI over time and there is regional structure in the metric.

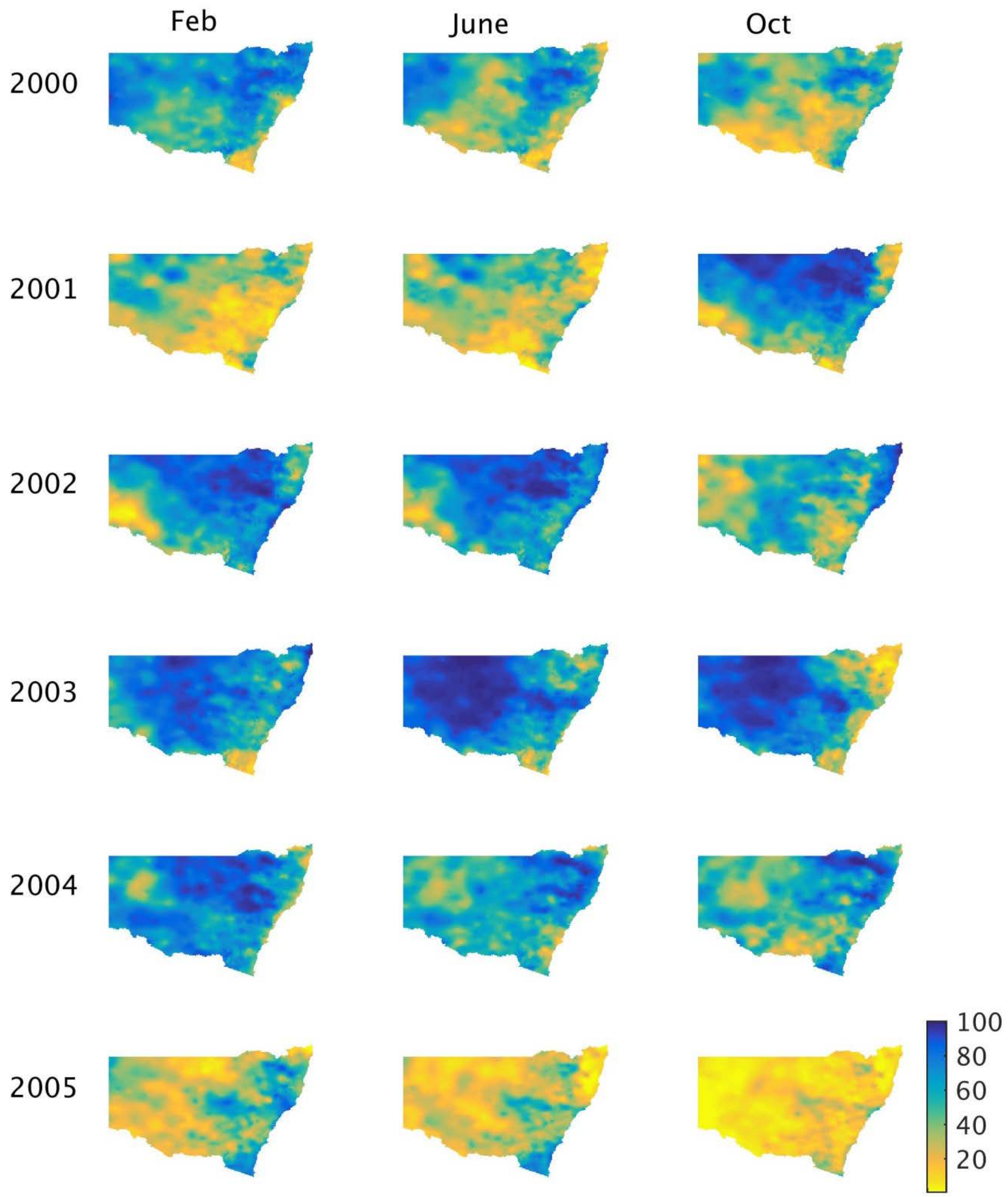

Figure 10. Example maps of the Rainfall Index (RI) value for mid-February, June and October for the years 2000-2005.

Time series of the SWI are in the same plot in Figure 9 (and Appendix 2), with spatial fields shown in Figure 11. The time series illustrate that the short range variability evident in the RI is not a feature of the SWI. The process of accumulation of soil water in the profile is reflected in the historical indicator, where the rate of decrease is slower than the rate of increase. This reflects the ability of some soils to store water with slow rates of loss from evaporation and drainage over 1-2 month period, compared to wetting events where the profile can be fully recharged given 1-3 days of moderate to high rainfall. Illustrative examples of these features are found in the time series (Figure 9) from 2002 through to 2005. Similarly, very intense rainfall events where there is a high degree of runoff do not overtly influence the SWI, addressing one of the concerns about rainfall effectiveness in drought monitoring. These properties of the SWI also have implications for its role in monitoring recovery in the CDI, where if soil moisture was the only indicator there would be a very rapid transition from drought through the recovery phases and into ‘Non Drought’ conditions. This provides one justification for developing a multi-indicator approach where agronomic recovery is considered.

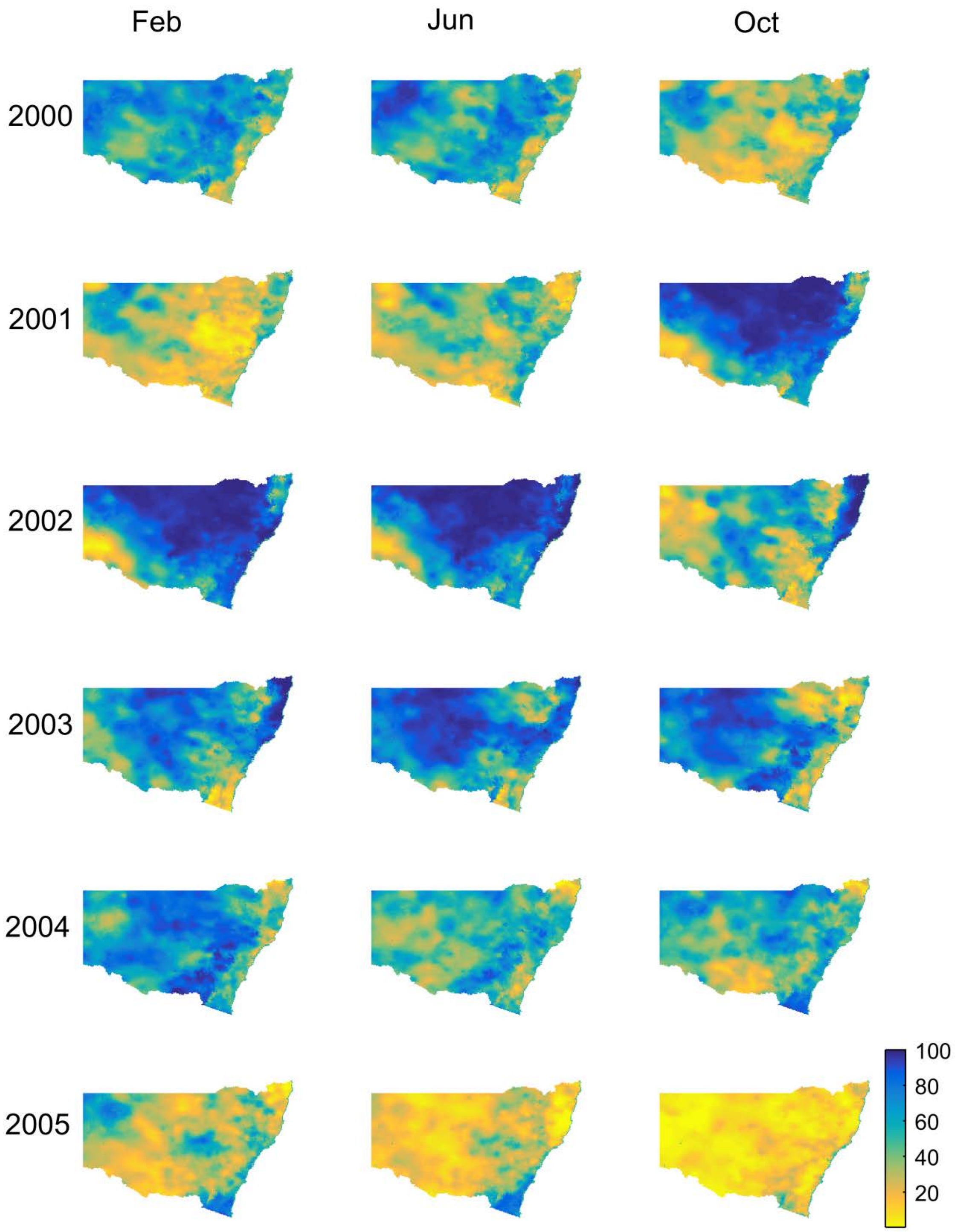

Figure 11. Maps of the Soil Water Index (SWI) value for mid-February, June and October for the years 2000-2005.

Time series of the PGI are presented in Figure 9 and Appendix 2, and like the SWI it has less short range variability than the RI. This agronomic indicator is not as responsive to an 'upside event' than the SWI, for instance close inspection of the rate of rise after 2005 in Beaconsfield in Figure 9 reveals it took some months for the PGI to transition from low to high levels, whereas the SWI took 1-2 weeks. However, while this is often the case in the time series it is not a completely persisitent property of the relationship between the SWI and PGI. There are other events in the sequence and in other locations where the SWI and PGI have a tighter, and also much looser, coupling.

Similar to the other indicies the spatial fields of the PGI are relatively smooth and continous (Figure 12). At this point it is worthwile considering the relationshiops between the spatial fields between the three indicators by examining Figures 10- 12. While there are similarties in the spatial structure of the data for the three metrics, there are fine level differences between their regional distribution. For example the soil moisture defecit indicated by low SWI values in the far west of the state in February 2000 is far more pronounced than the area of low rainfall (RI) plant growth response (PGI).

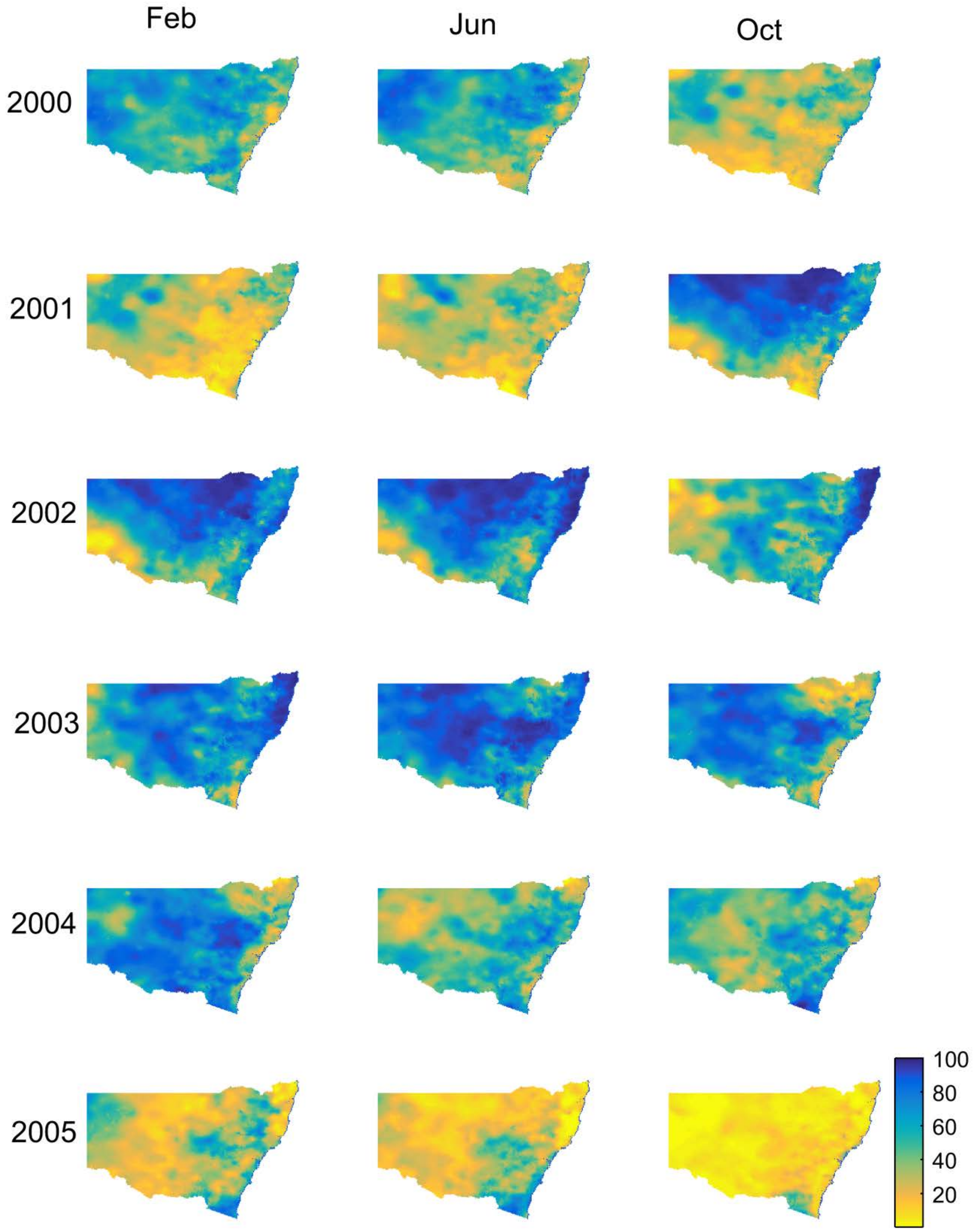

Figure 12. Maps of the Plant Growth Index (PGI) value for mid-February, June and October for the years 2000-2005.

Relationships between historical indicators

A formal analysis of the relationships between the historical drought indicators is presented in Figure 13. The top panel are matrix scatter plots of daily RI, SWI and PGI values from 1915-2015, visualising the relationships at the three illustration parishes. The bottom panel shows maps of the correlation coefficient, showing the regional distribution of the strength of the relationships for all parishes. The scatter plot matrices in Figure 13 visualise strong positive correlations between the indices at the individual parishes, and this appears to hold across the state with the mapped correlation coefficients constrained to a range of 0.70-0.99 in all parishes. This reflects the way the indices appear to be coupled in Figure 9, in that they track the same events and follow each other closer over time. This result is not unexpected as strong correlations between well founded rainfall, soil water and plant responses indices often emerge when processes are aggregated over long time periods (12 months in for the individual drought indices).

Given the presence of a strong positive relationship it is tempting to conclude that one individual drought indicator could be used to monitor drought, and that the multi-indicator approach in the CDI adds unnecessary complexity. However, inspection of the fine grained properties of the relationships reveals some important features in the context of defining drought for near real time monitoring. Firstly no individual drought indicator can be identified as a consistently leading or trailing index. As described previously the SWI may be falling more rapidly and earlier than the RI, while there are other examples in the past where the reverse appeared to be true (Figure 9). In terms of tracking the timing of entry and recovery from drought, these differences in the way the indices are coupled equate to variations of weeks to months for trigger a particular phase. For scientific purposes, such as analysing trends or developing long term drought probabilities, these types of differences are negligible. However, for operational purposes including drought declarations in regional areas as part of drought assistance, lags of 1-2 months are critical for mobilisation of resources and timing management responses.

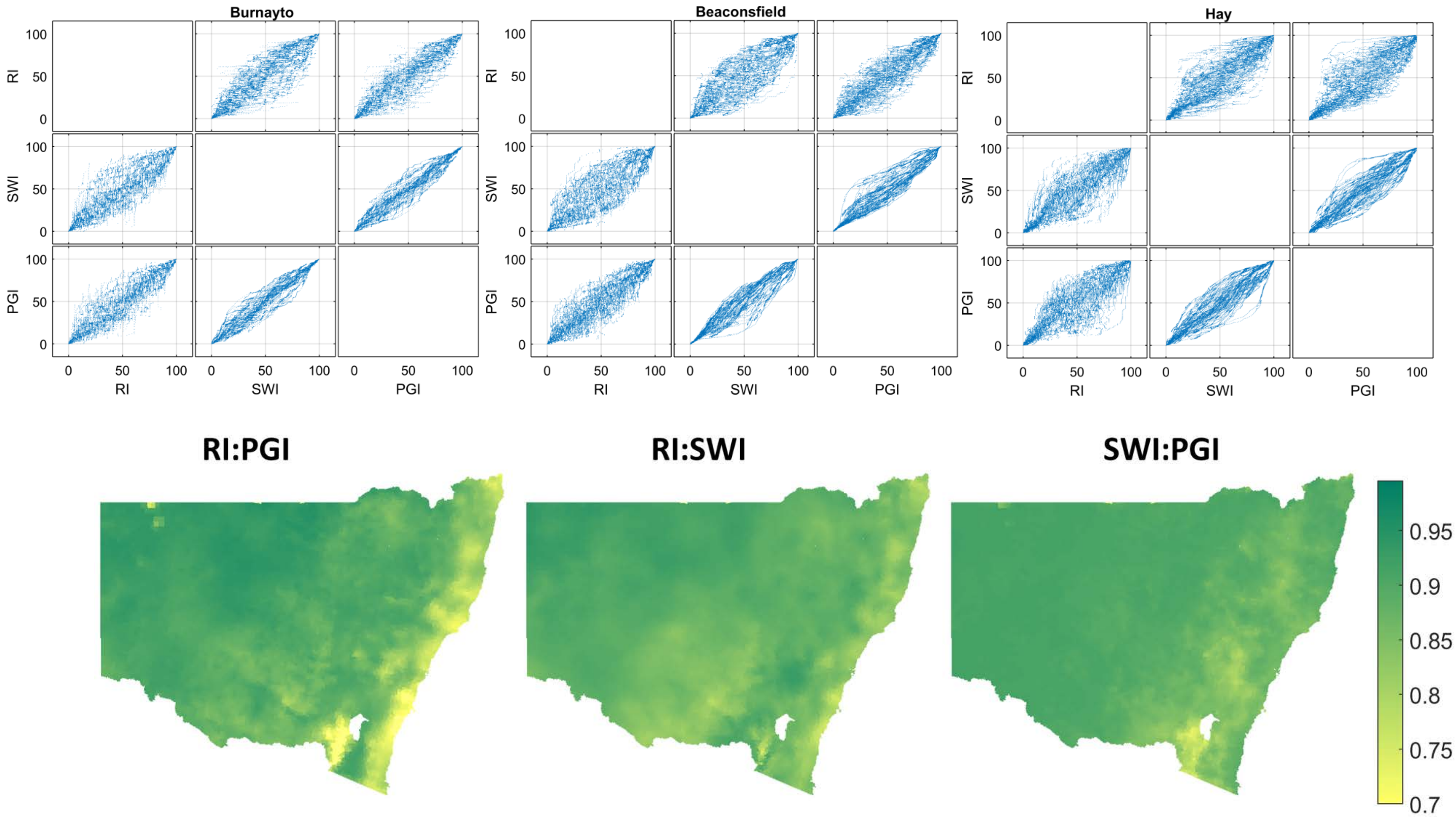

Figure 13. Correlation between the historical drought indices, Rainfall Index (RI), Soil Water Index (SWI) and Plant Growth Index (PGI) at A:Burnayto, B:Beaconsfield:, C: Hay (Top) and the spatial distribution of the correlation coefficient (bottom).

In the formal correlation analysis (Figure 13, top panel) the data has a structure where the strength of the correlation is proportional to the magnitude of the indices. The correlation between all indices is tighter at the lower end of the range, below the 10^{th} percentile, and at the upper end of the range, above the 90^{th} percentile. While there is a general positive relationship, data in the middle of the range has lower correlation, and there are structures in the data where the indices are coupled but well above or below a 1:1 relationship. This means that the indices are least similar during the 'Warning' and 'Recovery' phases of the CDI, where individual drought indicators can have large differences. This justifies the configuration of the CDI algorithm, where an 'or' rule is used to weight the CDI towards the lowest value index to define the 'Warning' and 'Drought' phases and with the 'and' rule providing the same weighting during recovery.

The high spatial correlation coefficients found across the state have been scaled in Figure 13 to assess if there is any spatial structure in the relationships. The relationships between the RI and the SWI, and to a greater extent the PGI, are lower in the coastal and alpine regions of NSW. These reflect a number of interacting factors such as the water storage capacity of different soils, and the thermal regime influencing the seasonal pattern of net primary production in crops and pastures. This re-enforces the multi-indicator approach as it is important to include information from an agronomic drought indicator in these zones to avoid bias.

Drought Direction Index

The Drought Direction Index (DDI) is plotted as a time series for the central reference site in Figure 9, while maps of the spatial field taken at the middle of the month for 1990-2010 are in Figure 14. These plots illustrate that the methodology used to construct the DDI provides a smooth continuous field in both space and through time, thereby satisfying a core property sought after for continued use. A range of trial and error tests were undertaken to examine alternative ways to configure the DDI, such as changing the aggregation window. Detailed results are not reproduced in this paper, as the main findings are encapsulated by the objective testing of the whole CDI framework described below. Importantly, the DDI is used in the CDI framework as a categorical not predictive indicator, as there is limited forward predictive skill in the metric when it is used in isolation. For example tests carried out at the illustration parishes showed that the probability of experiencing a drought in the next 1-3 months under a negative DDI is around 0.40-0.50.

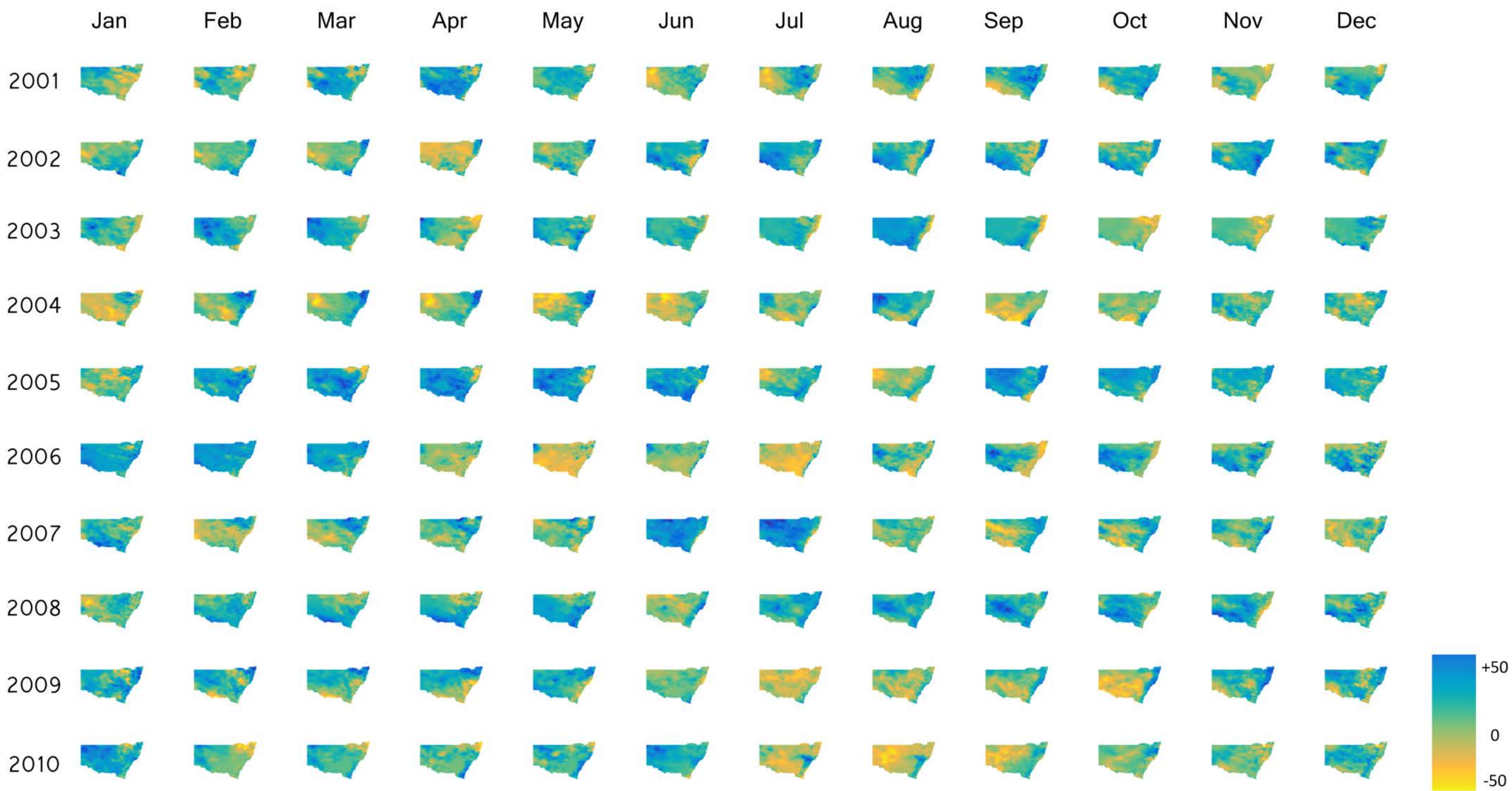

Figure 14. Maps of the DDI at the 16th of each month from 2001 -2010.

Objective testing

Sensitivity to indicator configuration

The outcomes of the experiments that systematically test the response of the CDI to changes in the configuration of the individual drought indices are in Figure 15. This is a matrix of time spent in drought for the period 1915-2015, mapped for all parishes, under a range of thresholds and aggregation windows. The outcomes of sensitivity testing, expressed as the change in time spent in drought for a 1 unit change in the percentile threshold (1 percentile) and aggregation window (1 month) are in Figure 16.

These tests establish that the CDI is highly sensitive to changing the historical threshold used to define drought. Working down the columns of Figure 15, time in drought shifts from less than 10 percent, to between 10-15 percent, through to 15-25 percent, when the threshold is set to the 5th 10th and 15th percentile respectively. This equates to a change between 1 to 1.5 percent of time spent in drought for every 1 percentile increase or decrease in the threshold. The most sensitive areas of the state are the south east central tablelands and coastal highlands where there is greater topographic influence on climate processes.

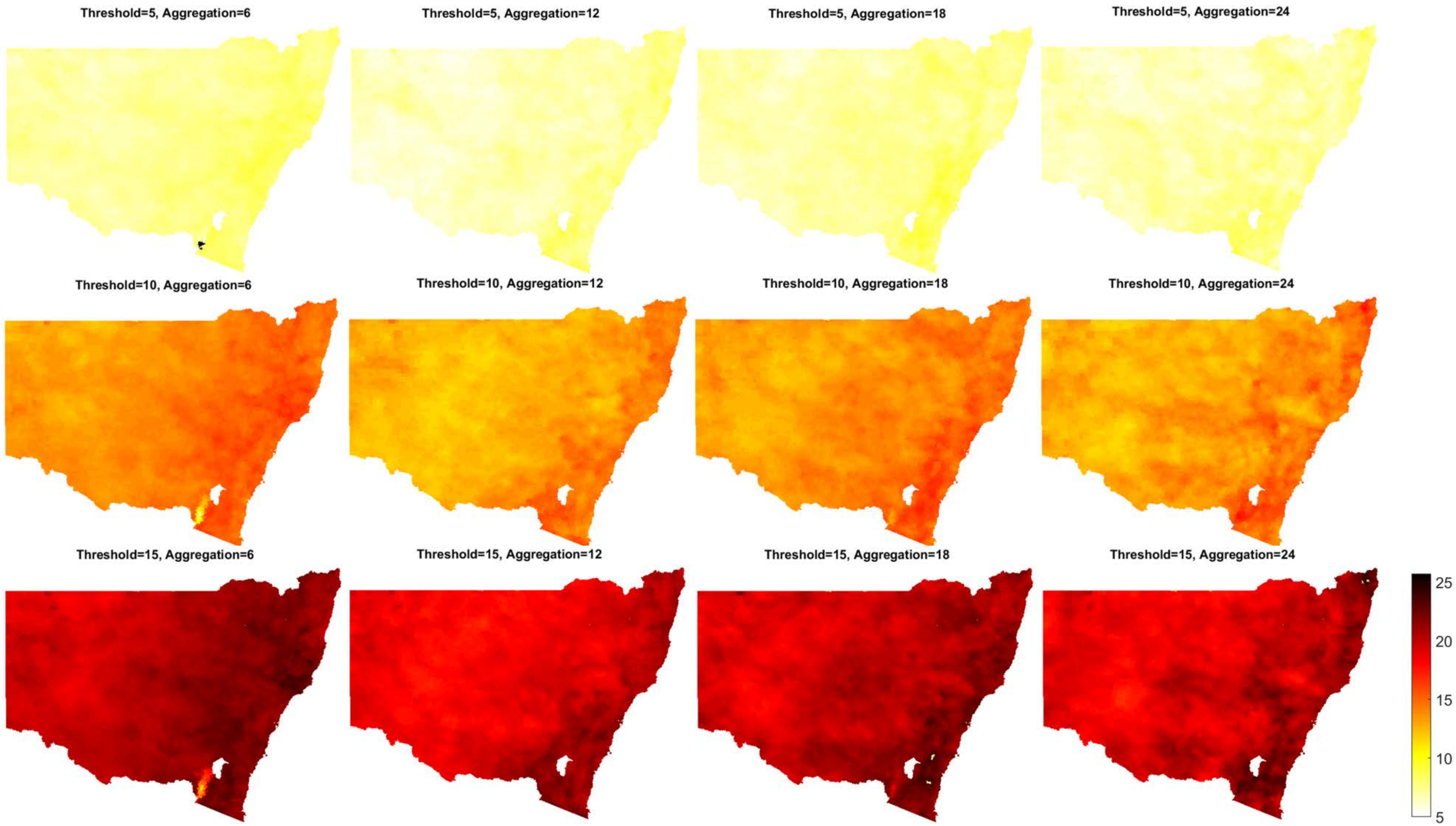

Figure 15. Matrix of time spent in drought (% of time 1915-2015) for a range of historical threshold and aggregation window values.

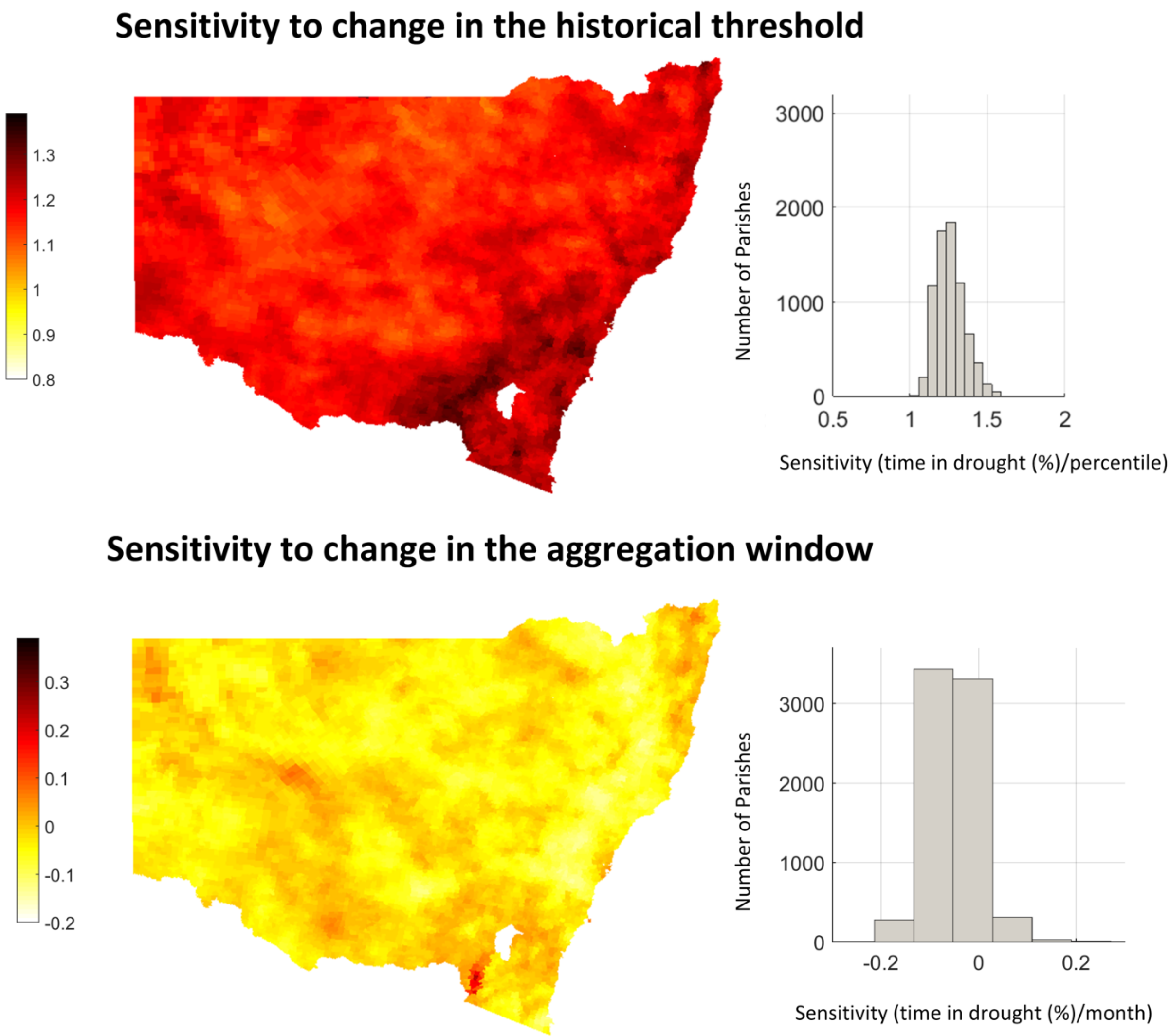

Figure 16. The sensitivity of time spent in drought (% of time 1915-2015) to a unit change in the percentile threshold (where the aggregation window is set at 12 months) and aggregation window (where the threshold is set at the 10th percentile).

Increasing the aggregation window from 6 out to 24 months had a relatively small effect on time spent in drought compared to changing the historical threshold (Figure 15). Moving across the columns in Figure 15, there are minimal changes to the spatial structure of the maps of time spent in drought for the different aggregation windows. There is a low sensitivity value across the state, a change between -0.2 to 0.2 percent of time spent in drought for a 1 month change in the aggregation window (Figure 16).

In the 6 month aggregation window (Figure 15) and the aggregation window sensitivity (Figure 16) there is a small area to the south east of the state where the time spent in drought metric appears to be substantially higher and more sensitive to change than surrounding regions. This is the Alpine zone of NSW where persistent cold temperatures severely limit production every winter, and a 6 month aggregation window is highly sensitive to this regular seasonal process. This feature is not present in the results when a 12 month or greater aggregation window is used, and the indicators appear less sensitive to seasonal processes.

While the time spent in drought is not overly sensitive to changing the aggregation window, an important timing effect is introduced when the aggregation window is changed. This is shown in Figure 17 where the percentage of the state in ‘Drought’ under different aggregation windows is shown as a time series for 2000-2010, including a finer granularity series focusing the 2002-03 drought. A 100 year series is (1915-2015) is provided in Appendix 2. These figures clearly illustrate that increasing the aggregation window delays the timing of drought onset, in terms of its representation by the CDI. Under the 6 month aggregation window in Figure 16 the 2002-03, drought starts to build in mid-2001, whereas the event starts building early in 2002 under a 12 month window. In contrasts the event starts to build well into 2003 under a 24 month aggregation window. A similar lag-effect is observable when examining how the event recedes under the different aggregations during the 2003-04 period. While lags of months appear small when examining patterns over a long time-frame (Appendix 2), they are important in near real time monitoring applications where delays of 3-9 months between indicators and field conditions are tangible for end users of drought monitoring.

In aggregate the analysis shows that the 6 month window is too sensitive to seasonal conditions and would lead to a highly unstable drought monitoring framework. The longer aggregation windows would effectively delay the responsiveness of the system. The 12 month aggregation window is the preferred option as it offers the best compromise between instability and delayed response.

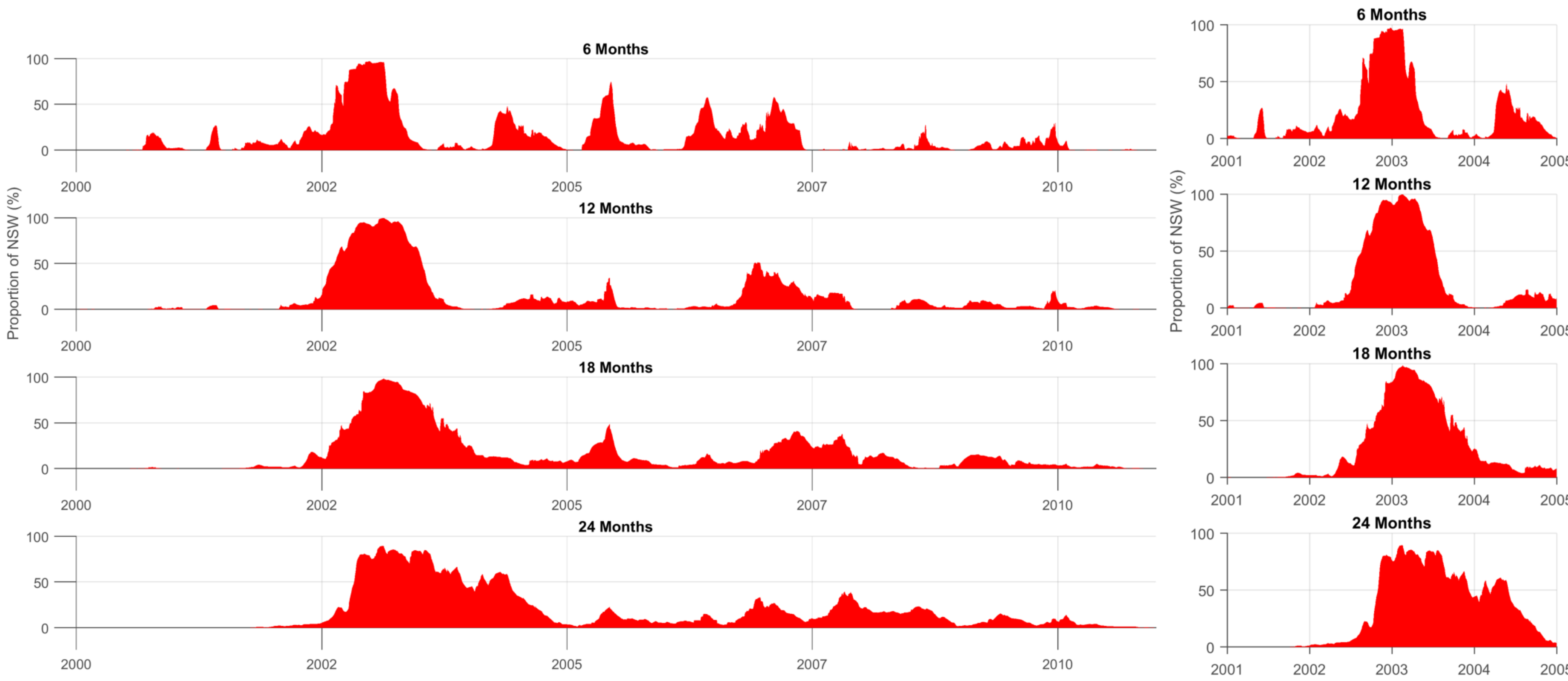

Figure 17. Proportion of NSW in drought when the historical drought indices are configured with 12, 18 and 24 month aggregation windows. Series from 2000-2010 with the period 2002-2005 inset. The 1915-2015 series is in Appendix 2.

Sensitivity to extending base period

Changing the base period used to establish the historical thresholds has a detectable but small influence on the CDI and its constituent indicators, as long as a period of 30 years or greater is used. Although the effects appear small, close inspection of the results highlights a shift in drought probabilities across NSW when the base period goes beyond 50 years, and this aligns with the shift in South East Australian rainfall patterns that occurred in the 1950's (Cai and Cowan 2013, Whan et al. 2014) and intensified from the 1980's through the Millennium drought (2000-2010).

To investigate the pattern of change further a second analysis is presented in Figure 19, where the probability of drought is calculated for different moving windows in time, of 10 years, 20 years and 30 years in length. This analysis is repeated at two levels, firstly the probability of widespread drought across NSW, defined here as droughts affecting greater than 2000 parishes, or approximately one third of the State or more. The second analysis relaxes this and includes all drought events that influence 100 parishes or more.

These analysis illustrate that there is strong decadal and multi-decadal signals in drought probability across NSW. For the 10 year window examining drought influencing more than 100 year parishes, the probability has peaked three times over the last 100 years, in the decades leading into the 1950's, the 1980's and again in the period leading up to 2010. Over a 30 year window there appears to be a downward trend in drought probability over time, which is more pronounced when the analysis is confined to widespread drought (affecting 2000 parishes or more). Cross referencing to the extended time series in Appendix 2 there is an increase in drought intensity and frequency (as measured by the proportion of the state experiencing drought) between mid-1930s to the late-1940's. This means that the trend in the 30 year window observable in Figure 19 may be an artifact of the starting point of the time series, and no analysis has been completed to test if it is a robust trend.

The implication for selecting base period is that a strategy to sample the range of decadal variability is likely to provide an adequate quantification of risk when setting base level thresholds in drought monitoring. This is captured by the 30-40 year window as long as it extends through the phases of decadal variability identified in Figure 19. This re-enforces the argument that a 'climatic normal' is an appropriate concept to guide baseline selection. In the case of the CDI this is set at 1985 to 2015, to include an appropriate recent sample of decadal variability. Given the small absolute differences identified in Figure 18 establishing critical thresholds using this period does not adversely change the probability of drought, although there are some minor regional differences.

Importantly the data used in the time series analyses in Figure 18 and 19 is based on a gridded climate product, and not on Australia's quality homogenised time series that are used to track long term trends. Further analysis of the long term decline in probability of widespread drought across NSW detected in Figure 19 is warranted to verify the validity of this result.

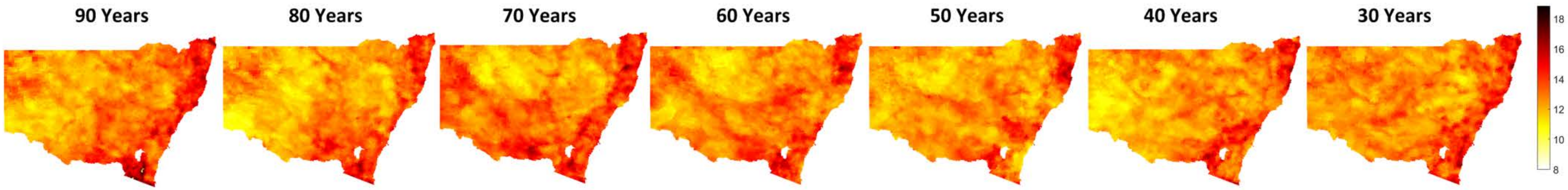

Figure 18. Time spent in drought (% of time 1915-2015) when the base period to determine the value of the 10th percentile is extended by 10 year increments from 30 years (1985-2015) back in time.

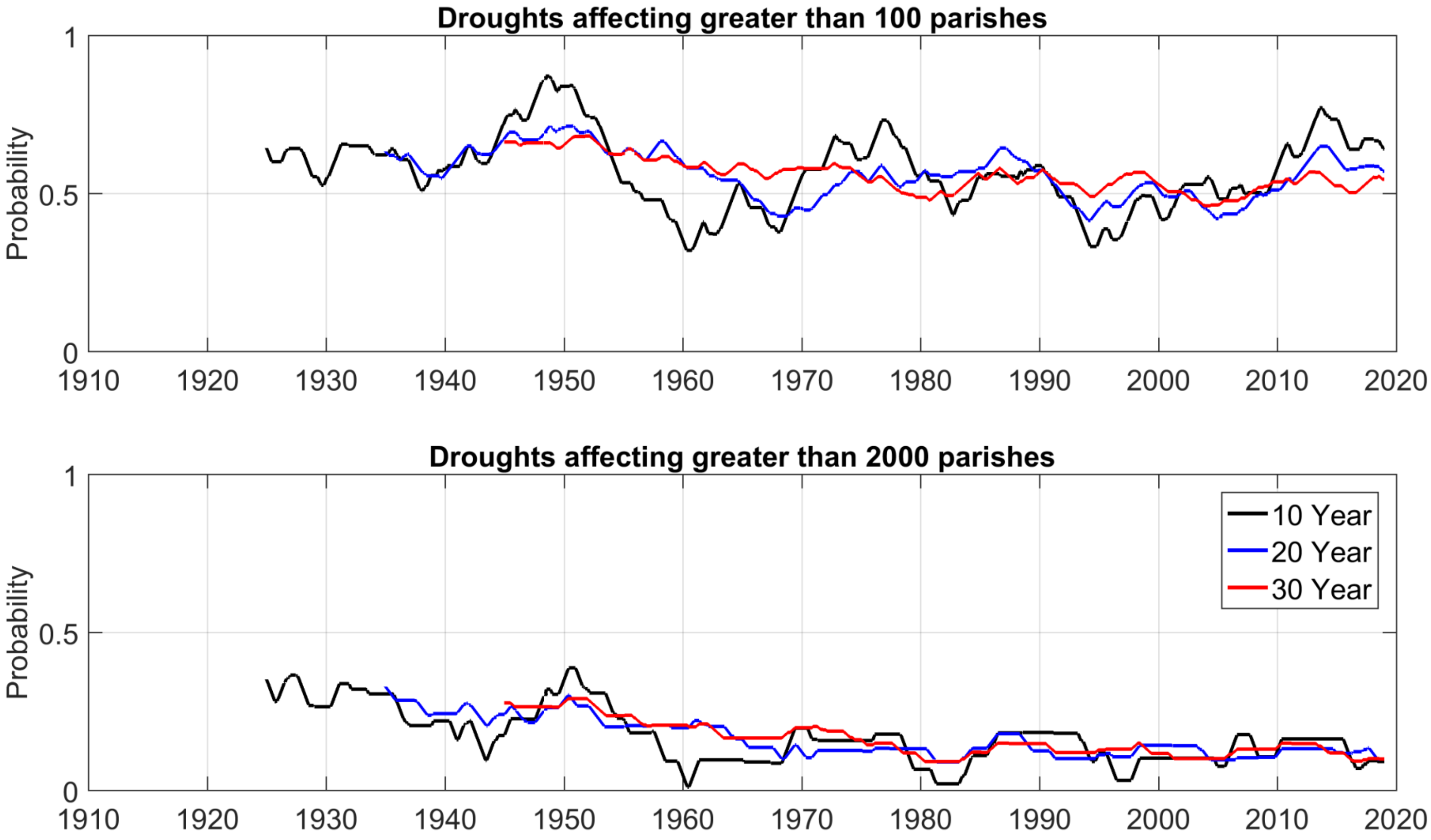

Figure 19. Probability of drought occurrence through time for 10, 20 and 30 year windows. Analysis of low extent drought (greater than 100 parishes or above, upper panel) and extensive drought (2000 Parishes or greater, lower panel).

Transition probabilities

The transition probabilities describing the likelihood of going from a ‘Warning’ into a ‘Drought’ phase over the coming month and three months (seasonal) are in Figure 20. The 1 month probabilities are low, with the most of the State having a 0.1-0.15 (10-15 percent) chance of entering a ‘Drought’ in the coming month once a ‘Warning’ has been issued. The chance of entering ‘Drought’ following a ‘Warning’ more than doubles when the window is extended to three months, with the bulk of the States parishes having a probability between 0.2 and 0.4 (20 to 40 percent). A small number of parishes are at levels above 40 percent, which could be considered a moderate to strong probability for a climate process. The data also has spatial structure, with the higher probabilities to the east, costal and particularly the south east of the State, with lowest values occurring in the central area of Western Division.

While the transition probabilities are low for one month, but increase over a three month forward period, they illustrate that there is some but not high levels of forward predictive skill available given knowledge of current climate conditions. The analysis does provide an insight into the potential value that seasonal forecasting of teleconnections and synoptic states of the atmosphere could provide if it could be integrated into the CDI, potentially be increasing these transitional probabilities to a level where they are more valuable for decision making.

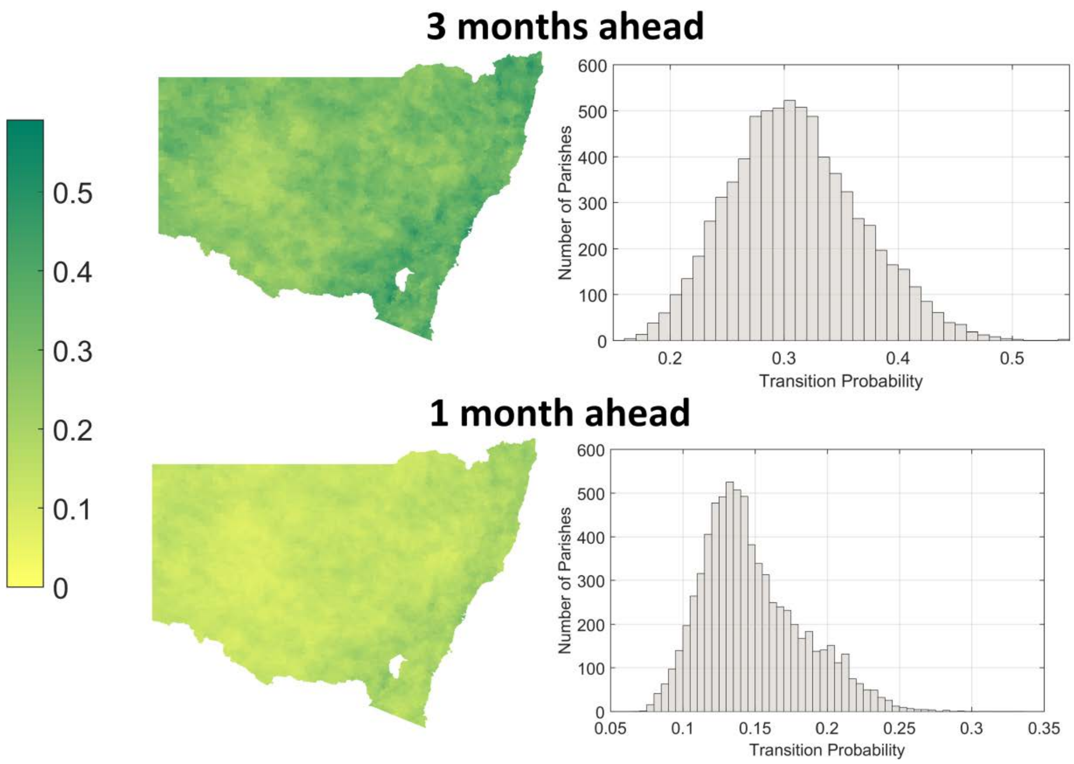

Figure 20. Transition probability for going from a ‘Warning’ into ‘Drought’ in the next month or over the coming three months.

Discussion

A theoretical framework for classifying drought into five distinct phases was initially posed, with the approach represented analytically using data and indices from EDIS, resulting in the Combined Drought Indicator (CDI). Testing the CDI under Australian conditions demonstrates that with careful selection and configuration of indicators, including a consistent approach to aggregation, a reliable and internally consistent tracking of drought as a phased process is possible using a multi-indicator framework. At a fundamental level the CDI algorithm tracks the partially random properties of drought events that are expected in Australia, which arise from the interaction of ‘chance mechanisms’ driving local rainfall and global forcing from mechanisms like the El Niño–Southern Oscillation (Gordon 1993).

In addition, configuring of the CDI with the Drought Direction Index (DDI) to identify ‘Warning’ and ‘Recovery’ phases provides the NSW Government with the capacity to monitor and respond early, and continue monitoring the event until a time that it has clearly receded. This contrasts to alternative approaches used in Australia that seek to distinguish ‘typical’ from ‘exceptional’ droughts. In these applications indicators configured with longer aggregation windows and lower percentile thresholds are used, effectively delaying policy recognition of an event, sometimes well past the drought onset phase. The CDI and EDIS provide a monitoring platform for the NSW Government to constructively engage stakeholders at an appropriate time in a complex and difficult to define climatic event.

Development and thorough testing of the CDI has provided some objective evidence to explore, and has taken some positive steps toward addressing, past criticisms levelled at Australian drought monitoring, in particular the ‘ad-hoc’ nature of declaration. For example, a positive yet inconsistent relationship was found between meteorological, hydrological and agronomic indicators of drought. For a scientific study seeking to establish long term baseline probabilities of drought occurrence, these differences are minor and choice of drought definition and subsequent indicator may not be critical. However in near real time monitoring applications the choice of definition and indicator is important as it influences the timing of drought entry and exit in the order of months. The decision rules forming the CDI provide a mechanism to reconcile these differences in a near real time application that is transparent, repeatable, and therefore likely to lead to a more equitable outcome for Government and stakeholders. This moves a monitoring system beyond the long running and sometimes controversial debate surrounding choice of drought indicators.

There is a complex relationship between meteorological, hydrological and agronomic drought indices. Despite a general overall correlation, there are times when the different ways of defining drought diverge and the differences are critical in near real time monitoring applications. There are periods of time when the CDI has difficulty in reconciling differences between ways of defining drought, particularly when indices are close to but do not cross critical thresholds. For this reason it is important to report the CDI with individual indicator values during operational use, so that the interpretation of variability and drivers of drought are transparent.

The 10th percentile has been chosen as the critical threshold for defining drought through an iterative dialogue between stakeholders and technical developers of EDIS, focussing on the insights provided by the sensitivity testing and subsequent implications of choices around thresholds. This means that NSW can expect to be in drought between 10-14 percent of the time, and this was considered to represent a fair and reasonable decision given the sensitivity of drought probabilities to threshold choice. Similarly a dialogue between stakeholders and technical developers guided the choice of the 30th and 50th percentile that define the recovery and normal phases of the CDI, as well as the decision to use a 12 month aggregation window. This follows the recommendation of Steinemann et al. (2005) who established that a more constructive approach to addressing operational indeterminacy was to enter a science-decision maker dialogue focussed on efficacy and implications, rather than attempting to prove which indicator or configuration is more or less scientifically correct.

A severe drought category has not been included in the CDI framework to move monitoring away from partitioning between ‘typical drought’ and ‘rare’ or ‘exceptional events’ as a way of targeting drought support. This is a departure from the approach that has been pursued in Australia for some time and has been heavily criticised. It mirror’s the advice of Stafford Smith and McKeon (1998) who advised that defining exceptional drought may be beyond the precision of modelling and climate monitoring in Australia. Frameworks like the CDI are best used for broad scale monitoring, early warning and coordination, rather than configuring them to identify the severity of events and using this as the main information set to administer drought support. In NSW, general level monitoring provides a valuable contribution to increasing the efficiency of the administrative system, but targeting drought support also involves individual property assessment using a range of socio-economic metrics.

The CDI has been configured to report at a spatial scale where the administrative boundaries are defined a-priori, thereby providing a consistent and transparent way to address the need to make subjective decisions about boundaries during a drought event. This contrasts to the use of regularised grids in reporting indicators for drought monitoring, where for further use in declaration decision, interpretation and potentially lengthy stakeholder consultation is required to place administrative boundaries around each drought event. The use of local parishes as a basis of monitoring and declaration isn’t new in NSW.

They are an ideal unit to represent the broad regional structure of drought events, but still capture locally specific variability as aggregates across 10-30 individual land holdings. However, the application of a consistent approach (algorithm) to this aspect of drought monitoring is new, and provides an automated and practical approach to implementation. While this has reduced the subjectivity of creating administrative boundaries around drought events, other problems need to be addressed to improve the local accuracy of drought declaration. For instance reducing localised error in rainfall data by increasing station density and improved modelling are positive steps.

A key technical insight established by the objective testing is that the proportion of time spent in drought is highly sensitive to changing the historical thresholds used to signify drought in indicators. This sensitivity has not been reported previously, and it is important, as drought monitoring in Australia has sought to discretise between ‘typical and ‘exceptional’ drought events by lowering the threshold value from the 10th to the 5th decile respectively. There has been a tendency to utilise drought maps based on different thresholds in declaration decisions, and-or develop decision support systems that allow users to adjust them. This provides the analytical mechanism for the types of incremental adjustments to drought declaration that have been identified as problematic in the past, without an understanding that the underlying probabilities of occurrence are being shifted dramatically.

While lengthening the aggregation windows did not affect the time spent in drought, it does create a lag which delays the near real time detection of events by 1-6 months. Similar to the use of different thresholds, there is a tendency to provide maps with different aggregation windows, and even combine shorter and longer aggregation windows in an attempt to track entry and exit, in declaration schemes. The results reported here establish that when combined with using different thresholds, this will create inconsistencies between drought phases and likely to re-enforce the ‘ad-hoc’ nature of declaration that has been identified in Australia. For operational implementation of the CDI in NSW it is therefore critical to move away from this approach, use the 10th percentile and 12 month aggregation window consistently, and not provide the facility for these aspects of indicator configuration to be adjusted during declaration decisions.

The overall insensitivity of time spent in drought to changes in the base period used to calculate historical thresholds was a surprising result given the presence of long term trends and the established links between trends in global climate processes and south east Australian rainfall (Whan et al. 2014). At one level it does re-enforce the concept of the ‘climate normal’ which underpins the WMO’s guidance about selection of base periods, where generally a period of 30 years captures enough climate variability to reproduce characteristic statistics like the 10th percentile reliably. The approach taken in the CDI to use the most recent 30 year window (1985-2015) to establish the historical thresholds, confines this to a period which includes recent climatic shifts and trends. This result runs counter to the advice of Hennessey et al. (2008) who cautioned against the use of deciles altogether, albeit using the full 100 year period, for quantifying drought in a non-stationary climate. Further study is needed on this technical aspect of the drought monitoring, aligned with building further knowledge of the influence of anthropogenic climate change on drought frequency, duration and severity internationally and in Australia (Milly et al. 2011; Sheffield et al. 2012).

Use of the term ‘normal’ to describe non-drought phases of the CDI is not technically correct, but was strongly advocated by stakeholders during the engagement process. Despite this, the term ‘Non drought’ was adopted after final consultation with the project’s Technical Review Group. This highlights one of the main tensions in developing drought monitoring frameworks, the interplay between the efficacy of terminology for stakeholder use and scientific and policy acceptability. In its current form the CDI is a compromise, and given the divergence of view uncovered in the sample of stakeholders engaged to develop EDIS, it is likely that universal acceptance of drought terminology may not be possible across the public stakeholder groups. For developers of drought monitoring systems it is important to note that settling the terminology is a challenging task in its own right. Depending on objectives and timeframes, there may be merit in undertaking market-based research and risk perception studies, in parallel with the technical development of drought monitoring systems.

While the CDI has taken some constructive steps to address the criticisms leveled at drought monitoring in Australia, many aspects of this system and drought monitoring in general, remain unanswered. Additionally, the framework also opens up opportunities for further development. Although the CDI provides a degree of early warning, information from a climate forecasting system is not included in the current approach. There is a depth of experience in the Australian research community, as in the 1980s and early 1990s some of the main causes and mechanisms responsible for drought were established, leading to improved predictability of the event (Stone 2014). Integration of forecasting into the EDIS system is technically feasible and will be valuable. This will enhance the early warning of drought provided by the CDI, although the framework will need to be adjusted to communicate probabilistic information.

While the objective tests implemented in this study identified how aspects of the CDI’s configuration influence the calculation of drought probability, there is scope to undertake a full sensitivity analysis to determine the influence of other uncertainties, such as the spatial and temporal error structure in the underlying climate data and biophysical model parameterisation. There is merit in considering the addition of a wet category into the CDI into the future, but care needs to be taken to align this with existing flood management in NSW, and carefully communicate its purpose so that it is not confused with a flood warning systems.

Similarly there is a strong rationale in drought monitoring to use socio-economic drought definitions and indicators which provide a metric that closely relates to impact on people and businesses (Kokic et al. 2007). This line of indicator development was not pursued in this study, because, as identified by White and Walcott (2009), socio-economic drought indices need to include factors other than climate, such as cultural settings, individual management decisions and prices, and near real time information systems are not readily available to track these factors at the scales at which climate is monitored. Opportunities emerging from ‘big data’ and IoT applications that enable producers and field staff to integrate their own information into a drought monitoring framework are a promising solution that could lead to the development of improved near real time socio-economic drought indices.

This study confirms the finding of others (see Sivakumar et al. 2014 for an overview) that it is important to objectively test how a drought indicator system performs before it becomes operational. Once a system has been embedded operationally it should not be altered in an ad-hoc manner during a drought declaration process. Unexpected and inconsistent results can occur given the complex interaction of the climatic and agricultural system, the drought indicator frameworks and policy decision making, where every drought event has a degree of uniqueness. While this conclusion appears to be logical, the implementation of drought frameworks in Australia has not always adhered to it (Botteril 2003; Keogh 2015) with well documented inconsistencies and unintended consequences for stakeholders (Productivity Commission 2008).

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Appendix 1. DPI Agri-Mod

Decsription

DPI Agri-Mod is suite of modelling algorithms and parameter libraries that have been developed to track indices of agricultural production at farm, regional and broader scales. The DPI Agri-Mod algorithms and libraries used for EDIS are the regional scale set. This provides a parameter efficient model that tracks the average response of agricultural fluxes at the effective monitoring scale of 1-5km^2. At this scale the average response provides a metric that is useful for tracking seasonal variability within a range of management and biophysical variability. Models that operate at this scale take a series of assumptions that simplify the system description, given aggregation of processes and or availability of input data, particularly around management inputs like fertilisation and stocking. This type of model is ‘conceptual’ in that while the algorithms are not fully mechanistic representations of the system they are also not empirical. This differs from paddock scale mechanistic algorithms used in agricultural system models like GRASP, APSIM and GrassGro, which have complex dynamics and are parameter intensive, so that they can explicitly predict the effects of changing or different management regimes at a sub-paddock scale. Optimisation techniques, usually applied to empirical approaches like regression or complex machine learning, can be developed for this type of model.

Algorithms

Growth

The primary algorithm is a modified structured similarly to the Gross Primary Production equation specified Kirschbuam (2015), which has been modified for grasses and the radiation use efficiency parameters are updated by remotely sensed NDVI. Here:

$$GPP = a\left(Q\left(1 - e^{-lv}\right)\right)[D](T)(W)$$

The left set of terms describe energy use-carbon assimilation, where *a* is the maximum pasture or crop production governed by nutrient levels and plant physiology, *Q* is photosynthetically active solar radiation derived from monitored radiometer data, *l* is the canopy area term derived from remotely sensed NDVI and *v* is stomatal function.

The rate of energy use-carbon assimilation is limited firstly by the thermal environment described by the term *T*. *T* is a function of the daily temperature regime where monitored maximum and minimum temperatures are constrained with crop and pasture specific parameters defining the minimum, maximum and optimum response thresholds as well as the photosynthetic pathway (for c3 or C4 species). *T* also includes a temperature damage term which limits carbon assimilation under frost conditions for some species.

The rate of energy use-carbon assimilation is also modified by water limitation (*W*) which is a ramp function based on plant available water (*PAW*). This describes the familiar allometric response of crops and pastures to water availability. *PAW* is obtained in the water balance described below. *PAW* is obtained from a three layer force-restore water balance based on Rickert et al. (2003).

The NPP equation contains an additional term for calculation of carbon assimilation of crops. This describes the development [*D*] of annual wheat based on the work of Angus (1981), with the structure defined by Lui (2007) and the crop development function in APSIM. The development coefficient [*D*] is a function of temperature and photoperiod through germination (G), emergence to floral initiation (S1), pre-flowering (S2) and flowering to harvest (S3) stages. G is determined by NDVI changes in the months April-June, while harvest is undertaken at 18 December thereby resetting the [*D*] value to 0 annually. The harvest date assumption is suitable when constructing drought indicators which are tracking potential climate limitations, but a specific date can be estimated to improve the prediction actual yields.

Parameter estimation procedure

The DPI Agri-Mod regional algorithms have been developed to address a number of known challenges in the application of spatial agro-meteorological models. Firstly the spatial estimation of soil and plant functional parameters is problematic. Farm scale systems models require of a-priori estimates of plant functional form and soil physics parameters, either by measurement, field scale calibration procedures or expert interpretation. These procedures are field and time intensive limiting the practical transportability of these models. While this is possible in localized case studies at single sites or regions, estimation across large regions has been problematic, as across NSW soil landscape variation is significant and there are broad ecological transitions defining the regional distribution of crop and pasture production. Pasture communities grade from sub-tropical in the north with greater prevalence of C4 grasses through to western land area where rangelands pastures dominate, through to temperate C3 grasslands. In the high rainfall zone micro-meteorological variation is significant given the effects of aspect and altitude.

An automated optimsation procedure was developed to solve the modelling framework and yield a set of state wide parameters (Figure A1.1). An objective function was formed as the weighted sum of squares (taking the Jacobian) between simulated values and the GPP values from 2000-2012, derived from the application of the diffuse model (Donohue et al. 2015). This was minimised initially by a pattern search algorithm to develop a trust region, then by a partial analytical method where the Jacobian was derived by finite differences. Initial guesses for the soil parameters were provided by the Australian Soil Landscape Grid

(Viscarra Rossel et al. 2015) and published vegetation responses (Nix 1071). The procedure was embedded as a large parallel processing experiment on a high performance computing mainframe, yielded a set of temperature, soil water and radiation use efficiency parameters across the state (Figure A1.2).

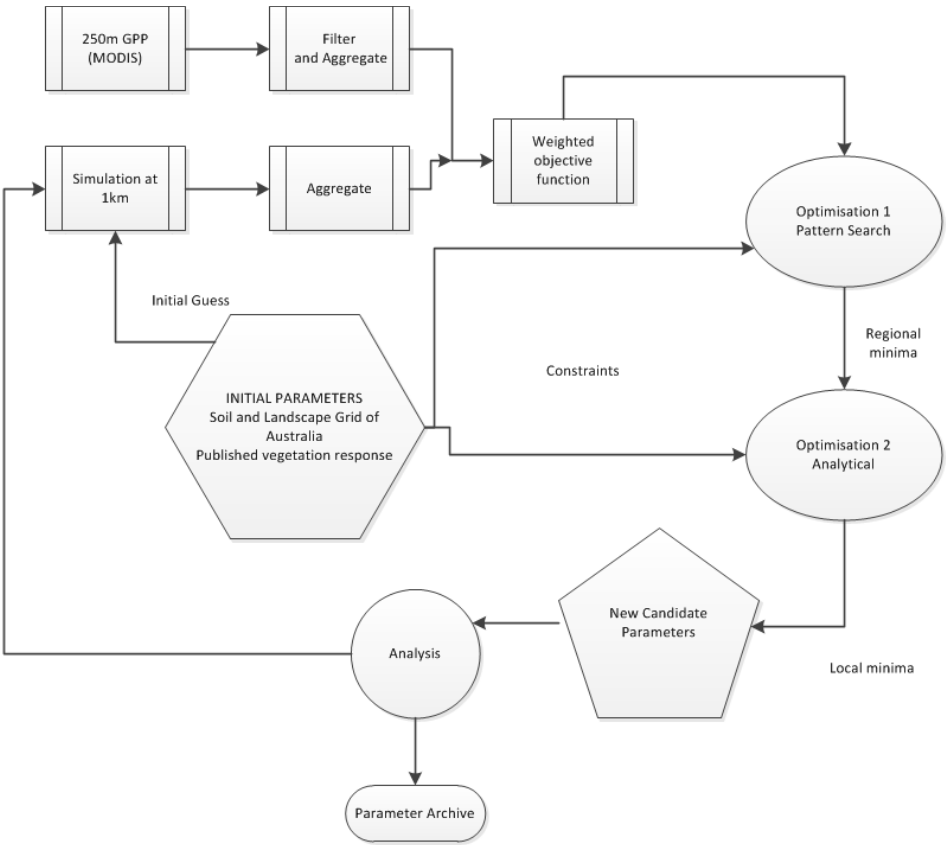


Figure A1.1. The optimisation workflow.

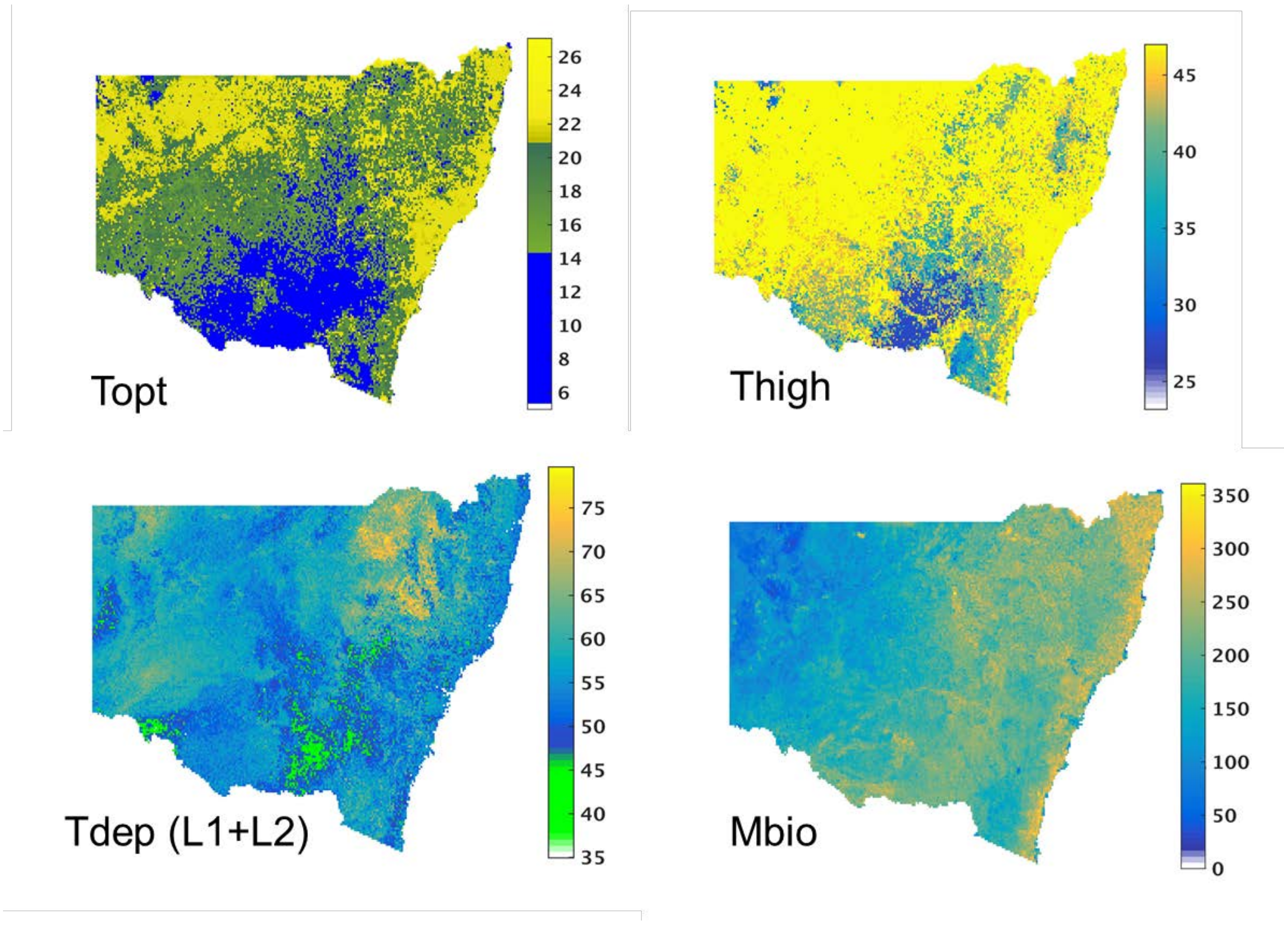


Figure A1.2. Optimal temperature parameters estimated for DPI Agri-mod for optimal temperature (Topt °C) and upper temperature threshold (Thigh °C), the soil water holding capacity of layers one and two (Tdep, mm) and the maximum biomass production (Mbio, GPP).

Independent verification of the model and parameters was carried out by comparing optimised output from DPI Agri-Mod against field observations collected at 41 pasture production experiments across NSW. The summary results, where values have been aggregated to monthly mean growth values are provided in Figure A1.3.

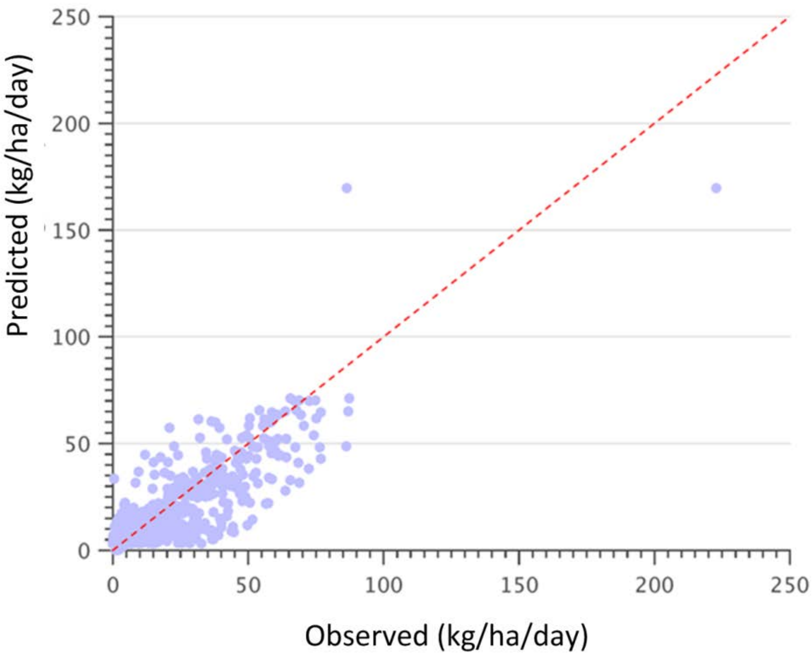
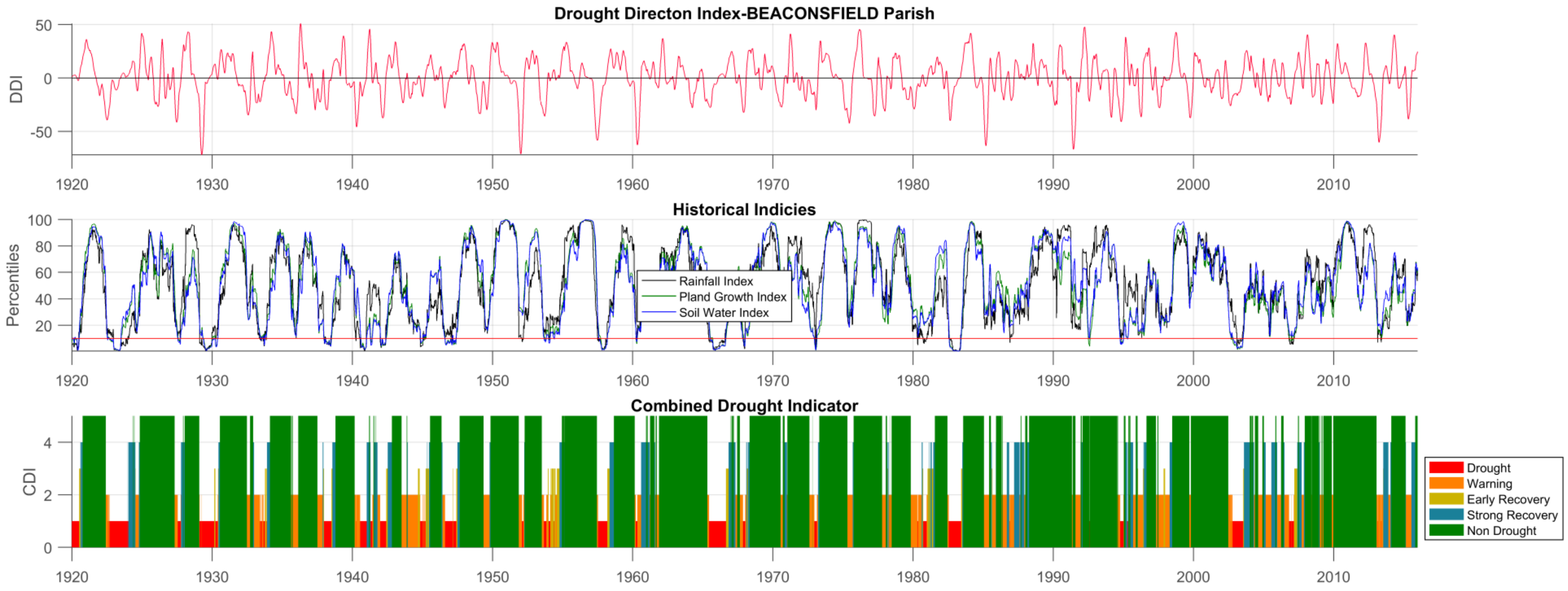
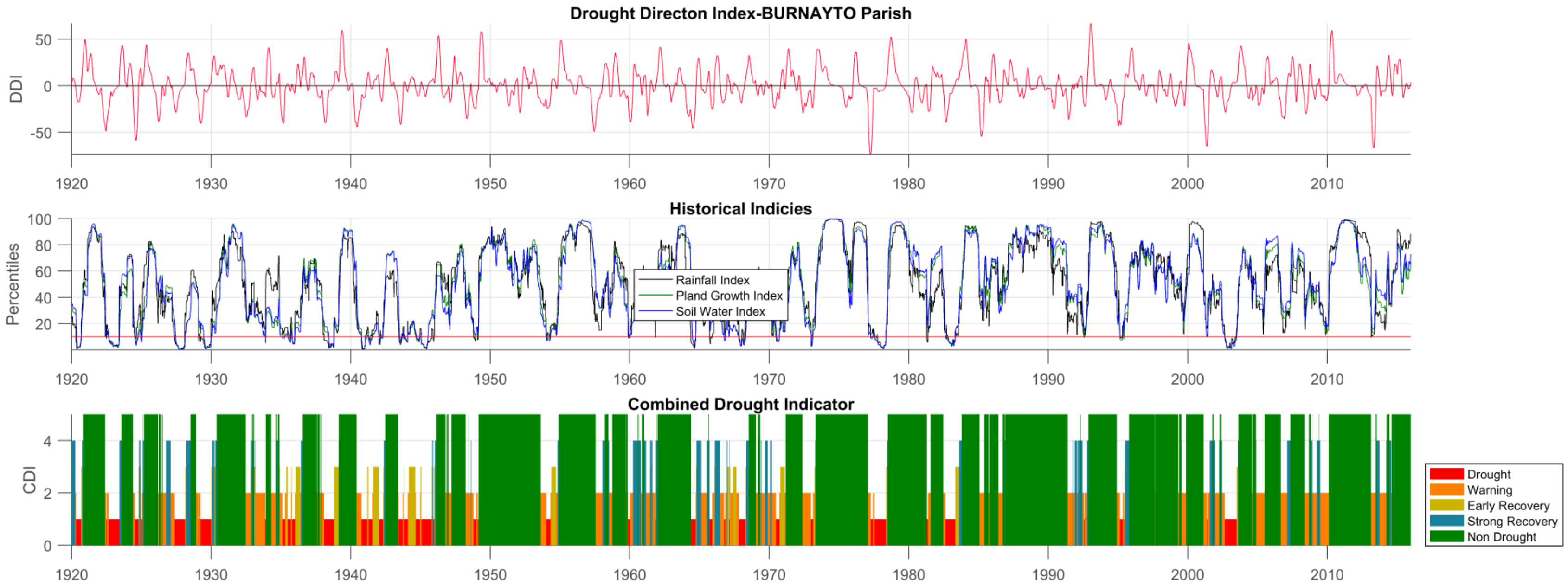


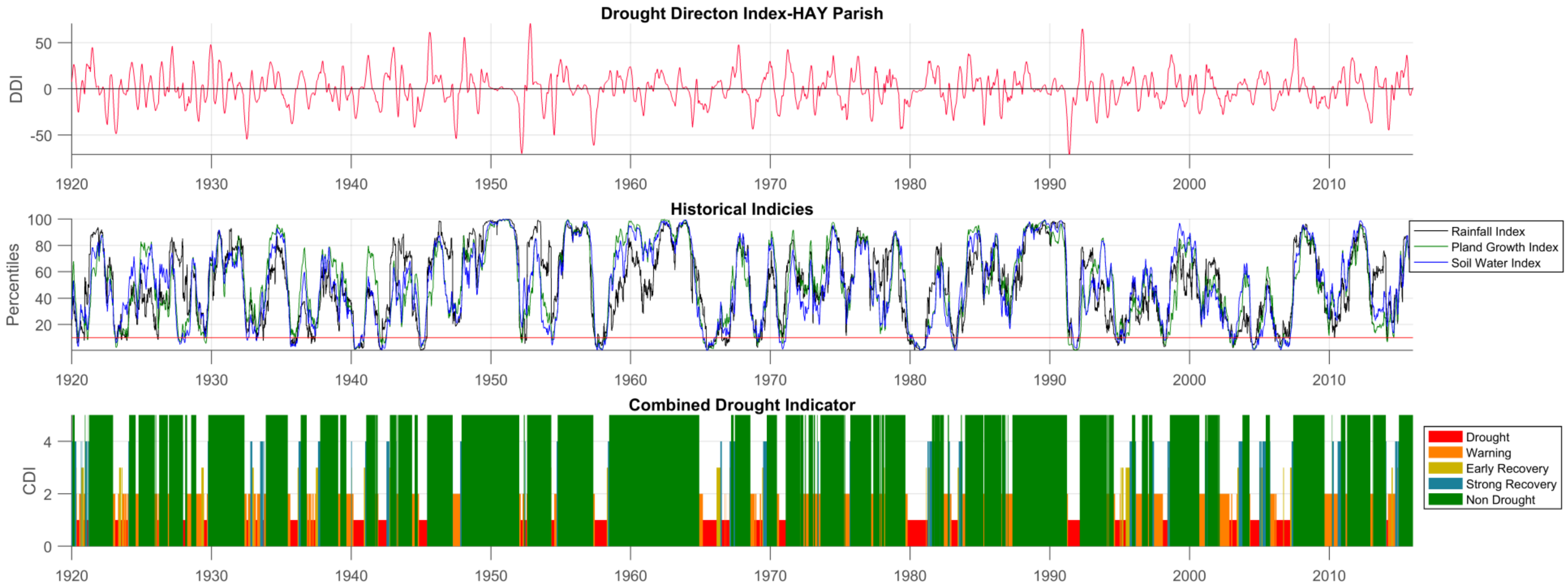
Figure A1.3. Example independent verification of DPI AgriMod: NSW pasture experimental sites.

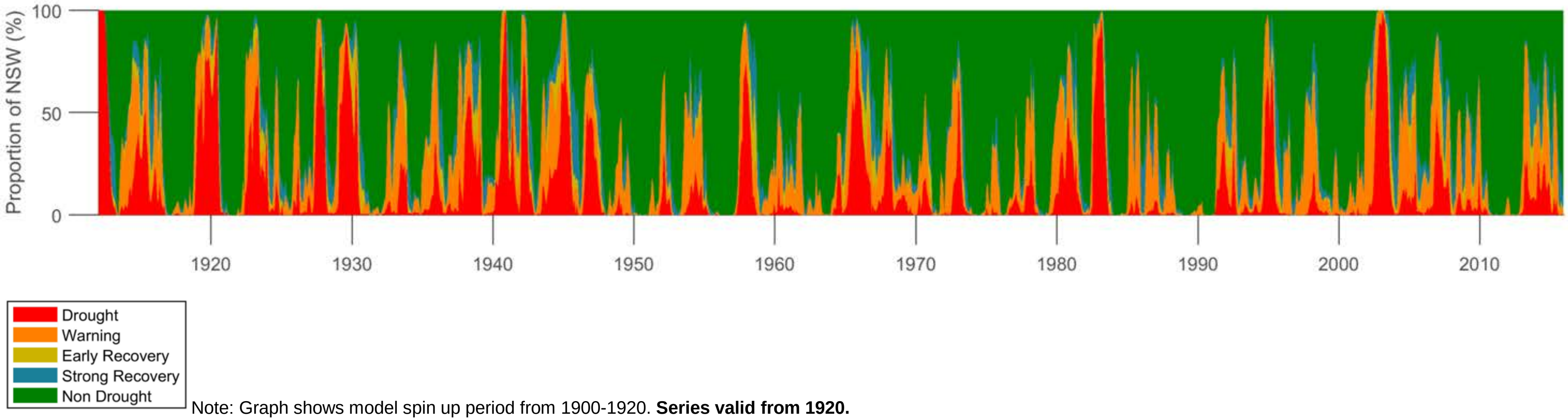
Appendix 2. Extended time series.


Drought Directon Index-BEACONSFIELD Parish
DDI
50
0
-50
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Historical Indicies
Percentiles
100
80
60
40
20
Rainfall Index
Pland Growth Index
Soil Water Index
Combined Drought Indicator
CDI
4
2
0
Drought
Warning
Early Recovery
Strong Recovery
Non Drought

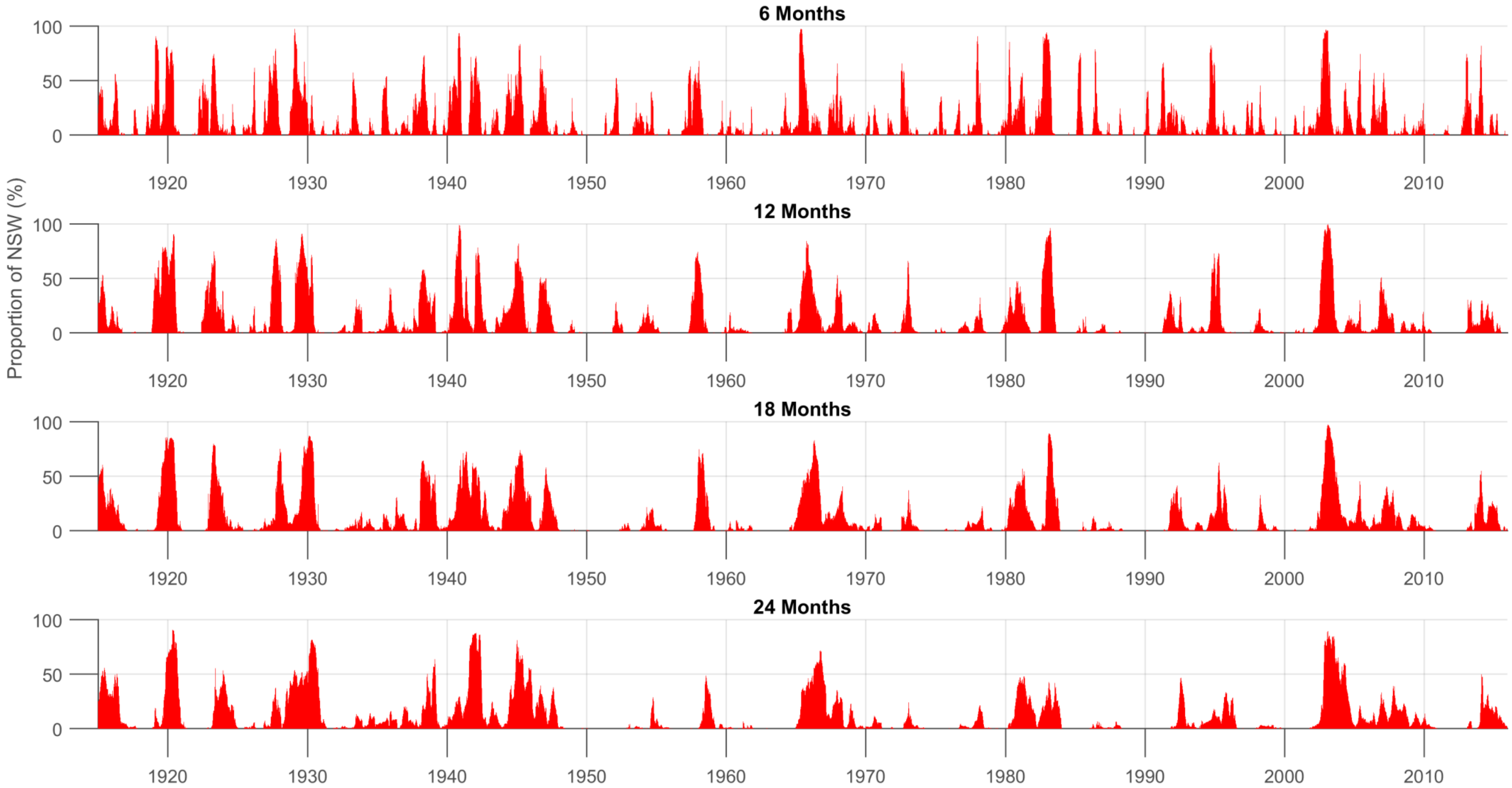


Drought Directon Index-BURNAYTO Parish
DDI
50
0
-50
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Historical Indicies
Percentiles
100
80
60
40
20
Rainfall Index
Pland Growth Index
Soil Water Index
Combined Drought Indicator
CDI
4
2
0
Drought
Warning
Early Recovery
Strong Recovery
Non Drought


Drought Directon Index-HAY Parish
DDI
50
0
-50
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Historical Indicies
Percentiles
100
80
60
40
20
Rainfall Index
Pland Growth Index
Soil Water Index
Combined Drought Indicator
CDI
4
2
0
Drought
Warning
Early Recovery
Strong Recovery
Non Drought



Note: Graph shows model spin up period from 1900-1920. **Series valid from 1920.**



6 Months
12 Months
18 Months
24 Months
Proportion of NSW (%)
100
50
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010