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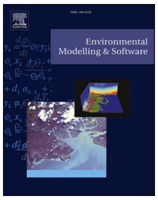

A drought monitor for Australia

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ABSTRACT

The UniSQ Drought Monitor and Australian Combined Drought Indicator (CDI) are introduced. The objective of these products is to use a multi-index approach to fully capture the long- and short-term consequences of drought as an information service for the public. Since drought is a complex phenomenon relying on multiple variables such as rainfall evaporative demand, and antecedent soil moisture conditions, monitoring drought using a single index or indicator is not always appropriate.

The Drought Monitor was developed using a normalized linear combination with weighting determined by PCA. It was evaluated against observed wheat yield as well as total pasture growth simulated by the Aussie-GRASS model. The results indicate that there was a significant positive correlation with both. The Drought Monitor was also well-received by survey respondents and has the potential to become a valuable drought monitoring tool for identifying drought impacts and related risks.

Software and data availability

Name of software: DroughtMonitor.

Developer: Laura Guillory (contact address: CSIRO Pullenvale Site, 1 Technology Ct, Pullenvale QLD, Australia; telephone +61 490 528 122; email: laura.guillory@data61.csiro.au)

Year first available: 2023.

Hardware required: Windows or Linux PC; Software requirements: Python 3, Anaconda, 7zip, Climate_Indices (Adams, 2017), and the following Python modules: python-dateutil, xarray, dask, netCDF4, numpy, Pillow, matplotlib, scipy, rasterio, rioxarray, Cartopy, cython, gdal, Fiona, toolz, bottleneck, requests, h5netcdf, shapely, Descartes.

Program language: Python.

Program size: 427 MB including installed Python modules.

Source code is available at: https://github.com/Laura-Guillory/DroughtMonitor.

The data that was procured to produce the online information service at https://nacp.org.au/drought_monitor is discussed in section 4.1: Data selection.

1. Introduction

In Australia, agriculture accounted for 55% of Australian land use at 427 million hectares, 11% of goods and services exports, 1.9% of value added (GDP) and 2.6% of employment in 2019–2020. Australian agricultural producers are required to manage a highly variable climate in addition to volatile commodity prices, which can result in a significant variation of farm output in return, which has major impacts on the wellbeing of agricultural producers and the Australian economy at large (Weragoda and Duver, 2021).

One of the greatest challenges for agricultural producers is the management of drought, which was demonstrated during the “Millennium Drought” in southeast Australia, described as the worst drought on record for that region. Prolonged below median rainfall had a considerable impact on agriculture, where irrigated rice and cotton production fell by 99% and 84% respectively between 2002 and 2009, and dryland wheat production saw a −12% per unit area decline compared to pre-drought years (Van Dijk et al., 2013). The impact of the drought on the Australian economy was dramatic, reducing the Australian GDP in 2002 by an estimated 1.6% and contributing to a rise in unemployment even in non-agricultural sectors (Horridge et al., 2005). The financial hardship introduced by severe drought has been demonstrated to

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contribute to a decline of mental health and wellbeing in rural Australia, with the effects most prominent among producers who have experienced the greatest impact on farm production (Edwards et al., 2015).

The recently released IPCC report predicts that the intensity and frequency of drought is likely to increase in Australia and many other regions due to climate change, and that it is possible that climate change has already contributed to an increase in agricultural drought in southern Australia (IPCC et al., 2021). Given that Australia also experiences a highly variable rainfall pattern, there is a clear need for accurate and accessible drought monitoring services in Australia.

There are already information services available to Australians that track a range of climate variables that are related to drought. The Australian Landscape Water Balance model (Frost et al., 2018), available on the Bureau of Meteorology (BoM) website, is an interactive tool which provides information about soil moisture, runoff, evapotranspiration, deep drainage and precipitation in near real time. Elsewhere on the BoM website, a page dedicated to reporting on drought (http://www.bom.gov.au/climate/drought/) includes spatial information for rainfall deficiencies, soil moisture, and total accessible water storage in the Murray-Darling Basin.

However, drought is a complex phenomenon which is difficult to capture with the monitoring of a single climate variable such as rainfall deficiency or soil moisture, and decision-makers may struggle with the task of interpreting the numerous climate variables available when attempting to build a picture on the overall state of drought. Australia lacks a comprehensive spatial data service with full continental coverage which can consider multiple climate variables to provide a snapshot of drought across Australia.

In New South Wales (NSW), the DPI Combined Drought Indicator (Clark et al., 2016) does take a multi-index approach, incorporating the Rainfall Index (RI), Soil Water Index (SWI), Pasture Growth Index (PGI), and Drought Direction Index (DDI). The DPI Combined Drought Indicator is published as an interactive tool (https://edis.dpi.nsw.gov.au/), providing a snapshot of current seasonal conditions and is one of the data sources used to inform policy and government responses to drought. However, its coverage only extends to NSW.

In the United States, the U.S. Drought Monitor (USDM) (https://droughtmonitor.unl.edu/) is available as an informative and easily understood composite product. The USDM is a joint effort by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Agriculture (USDA). Each map is designed by authors using expert judgement to blend local input, impact reports, and dozens of numerical indicators such as precipitation, streamflow, reservoir levels, temperature and evaporative demand, soil moisture, and vegetation health in a process described as convergence of evidence. The USDM was overall well-received due to its intuitive presentation of colour-coded maps, and its timely delivery as an operational online product (Svoboda et al., 2002; National Drought Mitigation Center, 2023).

The Australian Drought Monitor is an online tool that tracks the severity and spatial extent of drought conditions across Australia (available at https://nacp.org.au/drought_monitor), which was developed by the Northern Australia Climate Program (NACP), a fully integrated research, development and extension (RDandE) program which aims to improve the capacity of the red meat industry to manage drought and climate risk across northern Australia (Cobon et al., 2021). The Australian Drought Monitor was created with the objective of following the lead of the U.S. Drought Monitor and the DPI Combined Drought Indicator for NSW, to apply the benefits of multi-index drought monitoring techniques to the whole of Australia. The Australian Combined Drought Indicator (CDI) introduced in this study, which forms the basis of the Australian Drought Monitor, is a scaled-down version of the U.S. Drought Monitor, using Standardized Precipitation Index (SPI-3), Normalized Difference Vegetation Index (NDVI), Evapotranspiration (ET), and Soil Moisture (SM) data. These four variables were consolidated via a normalized linear combination and specifically calibrated to suit Australia's unique and varied climate using principal component analysis (PCA). The CDI was evaluated against crop yield, total pasture growth data and eyes on the ground in the form of producers, extension officers and Climate Mates associated with NACP.

2. Data and methods

2.1. Data selection

Four drought-related variables were chosen to be aggregated into the CDI – SPI-3, NDVI, ET, and SM. For the purposes of this study, these gridded datasets were standardised to a spatial resolution of 0.05° (~5 km) and aggregated to monthly data. The temporal coverage of the data is from April 1998 onwards, which is the extent of data available for NDVI due to the historical limitations of satellite data. All data sources were selected due to their temporal and spatial availability, their relevance to both short-term meteorological drought and longer-term agricultural drought, and their near real time updates, which allows the CDI product to be updated promptly each month. A brief description of each dataset is presented in the following sections.

2.1.1. Standardized precipitation index

The 3-month standardized precipitation index (SPI-3) was calculated using monthly precipitation data downloaded from the Scientific Information for Land Owners (SILO) database hosted by the Science and Technology Division of the Queensland Government's Department of Environment and Science (DES). The SPI was derived by fitting observed precipitation to a probability distribution function using a Pearson Type III distribution, that was then transformed to a normal distribution (J. Keyantash, 2018). The key strength of the SPI is its ability to characterize meteorological drought on different timescales, demonstrating that it is possible for a region to be experiencing favourable conditions in the short term while simultaneously suffering the effects of a preceding prolonged drought. Since one of the aims of this research was to explore the possibility of producing the CDI based on multiple timescales, the SPI was an attractive option as an input variable. The SPI variable used in this study was calculated for the periods of 3, 6, 9, 21, 24, and 36 months using monthly input data. Climate_Indices, an open source software package implemented in Python, was used to compute the SPI (Adams, 2017).

2.1.2. Normalized difference vegetation index

The Normalized Difference Vegetation Index (NDVI) is a simple indicator of the greenness of vegetation that has been widely used for ecosystems monitoring. The NDVI calculates the difference between visible (red waveband) and near-infrared (nir) reflectance (ρ) of vegetation cover formulated as $= (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red})$. The ratio provides a measure of density of green on an area of land where its values range from −1 to 1 (Weier and Herring, 2000). Higher NDVI values indicate a higher density of green vegetation while low values indicate moisture-stressed vegetation and hence it can be used for drought monitoring and warning. The NDVI data used in this study was acquired from Copernicus Global Land Service (https://land.copernicus.eu/global/products/ndvi). It is available as an annual archive at a resolution of 0.01° (~1 km), and as a near real time dataset (within 3 days after synthesis period) at a resolution of ~300 m. In order to compromise between file size considerations and temporal coverage, both datasets were merged for use in this paper after being aggregated to monthly and resampled to a resolution of 0.05° (~5 km). This is a global dataset but was subset to cover only Australia for the purposes of this study.

2.1.3. Evapotranspiration

The evapotranspiration (ET) dataset was acquired from SILO, Queensland Department of Environment and Science (DES) (https://www.longpaddock.qld.gov.au/silo/). The datasets are constructed from observed data obtained from the Australian Bureau of Meteorology (BoM) and other suppliers. The ET values were calculated using the Penman-Monteith (PM) equation, which was suggested by the United Nations Food and Agriculture Organisation in their Irrigation and Drainage paper no. 56 (FAO56) (Allen et al., 1998; Webb, 2010). The calculation of ET using this FAO56-PM method was based on a standardized vegetated surface, i.e., a standard "reference" crop and hence often referred to as "reference crop evapotranspiration" or "reference evapotranspiration", denoted as ET_0. Estimation of evapotranspiration for different crop types (ET_C) was acquired by multiplying the ET_0 by a crop coefficient K_C, i.e., $ET_C = ET_0 \times K_C$. The ET used in this study is a short crop estimate that was interpolated to provide a 5 km data grid across Australia. Daily ET data was then aggregated to monthly data.

2.1.4. *Soil moisture*

The soil moisture (SM) dataset was downloaded from the Bureau of Meteorology (BoM) (http://www.bom.gov.au/water/landscape). The data was estimated by summing the available water content of the upper and lower soil layers in the Australian Water Resources Assessment Landscape (AWRA-L, version 6.0) model (Viney et al., 2015). The soil moisture dataset used for the CDI is “root zone soil moisture”, which represents the percentage of available water content in the top 1 m of the soil profile. The maximum water storage of the root zone is calculated using the depth of the soil and the relative soil water storage capacity, which is derived from soil properties that are mapped within the Australian Soil Resources Information System (Johnston et al., 2003). Only data from 2000 to present is available for download on this page, however the complete model output (1911 to present) is available on request. Data is available at a resolution of 0.05° (~5 km) and aggregated monthly.

2.1.5. *Data for evaluation*

Data for evaluating the CDI were obtained from farm surveys conducted by the Australian Bureau of Agricultural and Resources Economics (ABARES), which provides a wide range of information on the performance of a number of sampled farms across the rural sector (ABARES, 2021b). Data for wheat production per hectare (t/ha) were collected from the AgSurf interface (ABARES, 2021a), ranging from 19981999 to 2019–2020 across a number of broadacre regions. Total simulated pasture growth data were collected from the AussieGRASS model published by LongPaddock (2021a). Pasture growth is defined as new above-ground plant material produced each month, measured in units of kg of dry matter per hectare (LongPaddock, 2023). This dataset was selected because of its availability and drought vulnerability. Lastly, the CDI was evaluated against the DPI Combined Drought Indicator for NSW using archive data obtained from the Seasonal Conditions Information Portal (SCIP), which was available from 2016 to 2021 (Department of Primary Industries, 2023a).

3. Methods

3.1. *Rationale for software design*

There were several important requirements that influenced the design of the Drought Monitor software.

- The ability to handle a large volume of raster data, given the spatial and temporal resolution of the data, the time period included, and the inclusion of multiple versions ranging from 1 to 36 months
- The desired spatial resolution was 0.05° (~5 km), and any datasets which were not initially available in this solution may need to be downsampled.
- A range of temporal resolutions would be required, which would represent an average of conditions over the previous 3, 6, 9, 12, 24, and 36 months. These results would be used to explore whether users found it useful to have a snapshot of long-term drought to assess the risk of long-term impacts such as reduced groundwater or ecological damage.
- Maps must be visually intuitive for the general public, featuring a colour-coding system to represent different levels of drought severity and categories of drought severity that are practical for decision-makers
- Automated monthly updates should be facilitated by the software, and results should be produced within a reasonable timeframe once data sources are made available each month
- Scripts should be generic enough to allow easy changes to configuration, data sources, and the visual design of maps

3.2. *Software design*

The DroughtMonitor software package was written in Python and made use of the xarray and dask modules, which were necessary to handle a large volume of Network Common Data Form (netCDF) data. Data retrieval, pre-processing, CDI computation, and visualisation are handled by individual Python scripts which have been constructed to be highly configurable to facilitate future adaptations. Since this software was designed to be run on a high performance computer (HPC), it is driven by Portable Batch System (PBS) scripts which determine the order of tasks, run configuration, and which tasks can be run concurrently. Fig. 1 shows the flow of data through the DroughtMonitor software package, which occurs monthly to update the online service.

First, data is retrieved from SILO, AWRA-L, and Copernicus using the *download.py* script. Any previously downloaded files are skipped (excluding data relating to the current year). Data is stored on UniSQ’s HPC for further use. In addition to the variables required to produce the CDI (*ndvi, monthly_rain, et_short_crop, max_temp, min_temp*, and *soil_moisture*), all datasets available on LongPaddock’s SILO are included as options.

The *prep_files.py* script then handles any pre-processing that is required, such as combining historical and recent data, subsetting to the relevant region, and downscaling to the desired spatial and temporal resolutions. The open source *climate_indices* Python package is then used to compute the SPI using precipitation data, as described in Section 4.1.1.

The process for computing the CDI involves normalising all variables using percentile ranking, grouped by geographical location (latitude and longitude), and month of the year. The baseline period used for percentile ranking is from April 1998 (earliest available NDVI data) to the present, which is applied to all variables for consistency. The baseline period extends to the present because percentile ranking can be vulnerable to granularity issues if few years are available, and the addition of new years in the future will reduce the effect. The $CDI_{y,m}$ for a particular year y and month m was formulated as a normalized linear combination of the four predictors and their weights (i.e., percentage contributions of each variables), $CDI_{y,m} = w_m^{ET} \times (1 - ET_{y,m}) + w_m^{NDVI} \times NDVI_{y,m} + w_{y,m}^{SM} \times SM_{y,m} + w_m^{SPI} \times SPI_{y,m}$ (Eq. 1), where w denotes the weight of each variable, which was determined using principal component analysis to achieve maximum variance, as detailed in Section 4.2.3. In all input variables except ET, a high value is associated with wet conditions and a low value was associated with drought conditions. However, in the case of ET, the opposite is the case. Therefore, it was appropriate to reverse the values of the ET dataset when incorporating it into the CDI, as expressed in Eq. (1). Following the computation of the CDI, the result is then again normalized using percentile ranking.

Prototypes of the CDI for rolling time windows of 3 months, 6 months, 9 months, 12 months, 24 months, and 36 months were also produced by aggregating the input variables to the appropriate time period before computing the CDI, with the exception of the SPI, where the SPI of the appropriate timeframe was substituted (i.e., SPI-6 instead

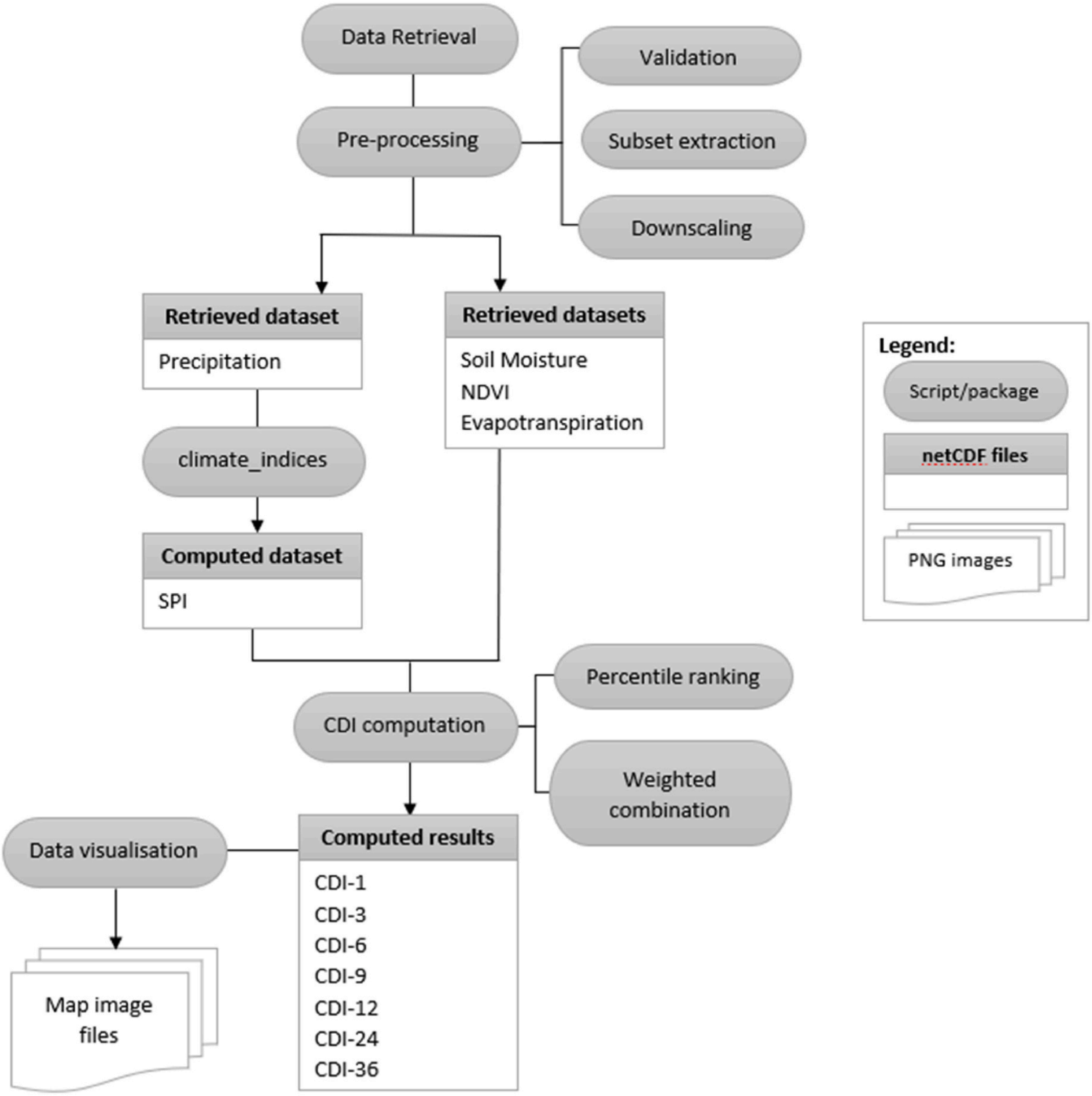

Fig. 1. Flow diagram of the DroughtMonitor software package used to compute the CDI.

Table 1
Category definitions for the monthly Drought Condition & Impact Report web-based survey.

Category	Definition
Exceptional wet	Water levels in dams, lakes, rivers and creeks are well above normal. Standing water covers large areas that are normally dry. Soil is completely saturated. There is widespread flooding.
Extreme wet	Water levels in dams, lakes, rivers and creeks are above normal. Standing water covers some areas that are normally dry. Soil is wet and the ground is completely saturated. There may be flooding.
Severe wet	Water levels in dams, lakes, rivers and creeks are just above normal. Standing water covers some low-lying areas that are normally dry. The soil is wet.
Moderate wet	Local plants, crops or pastures are healthy and lush. The soil is damp. Water bodies may be fuller than normal.
Slightly wet	Local plants, crops, or pastures are healthy, recovering from dry conditions. Soil moisture is above normal.
Near normal	What you are seeing is what you expect for this time of year.
Slightly dry	Growth may have slowed for plants, crops, or pastures. The soil is somewhat dry. Local plants, pastures, or crops may not have fully recovered if conditions are changing from drier to wetter.
Moderate drought	Plants may be brown due to dry conditions. Dams, lakes, rivers, and creek water levels may be low. There may be water shortages. Plants, crops, or pastures may be stressed. The soil is dry.
Severe drought	There is no soil moisture. Dams, lakes, rivers, and creeks may be nearly empty or dry. Producers have crop or pasture losses.
Extreme drought	There is no soil moisture. Dams, lakes, rivers, and creeks may be nearly empty or dry. Producers experience widespread crop or pasture losses. They may be wind erosion due to lack of vegetation cover.
Exceptional drought	There is no soil moisture. Dams, lakes, rivers, and creeks are empty or dry. Producers experience widespread crop or pasture losses. They may be more wind erosion due to lack of vegetation cover.

of the SPI-3). They will be referred to as the CDI-3, CDI-6, CDI-9, CDI-12, CDI-24, and the CDI-36.

3.3. Determining the optimal weighting

The optimal weight of each input variable was estimated using PCA. This method was chosen to ensure that the contribution of each input variable could be quantified objectively. The baseline period used for PCA was from April 1998 to November 2020, when the weights were computed.

The correlation coefficient matrix of four ranked time-series variables were used to compute the eigenvectors. The eigenvectors E are unit vectors that were used to transform the original variables X into orthogonal principal components (PCs) Z expressed in a matrix form $Z = XE$. In this study, we use the eigenvector associated with the first PC that captures the maximum variance of the four variables to determine the optimal weightings. More specifically, the weight of each variable used to calculate the CDI was derived by taking the squared value of the first eigenvector to minimize anomalous (peak or spike) values observed in the process of developing the index (Bayissa et al., 2019).

The computed weights are retained between updates rather than being refreshed each month, and so is not included in the DroughtMonitor software package.

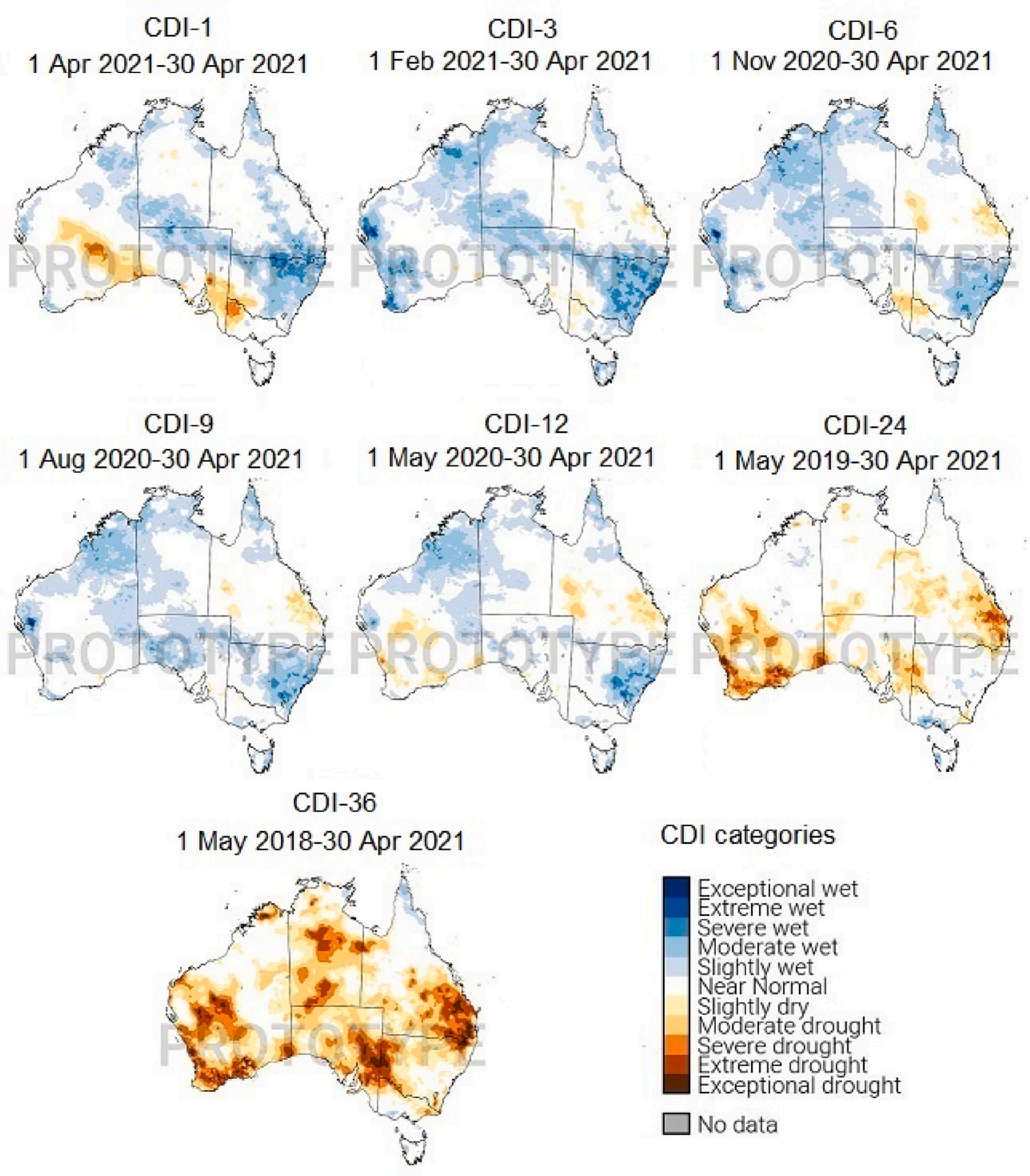

Fig. 2. Final product of the Australian Combined Drought Indicator (CDI), featuring the 1-month CDI (CDI-1), 3-month CDI (CDI-3), 6-month CDI (CDI-6), 9-month CDI (CDI-9), 12-month CDI (CDI-12), 24-month CDI (CDI-24), and 36-month CDI (CDI-36).

Table 2
Australian Combined Drought Indicator (CDI) categories based on percentile rank values.

Value	Category
<0.02	Exceptional Drought
0.02–0.05	Extreme Drought
0.05–0.1	Severe Drought
0.1–0.2	Moderate Drought
0.2–0.3	Slightly Dry
0.3–0.7	Near Normal
0.7–0.8	Slightly Wet
0.8–0.9	Moderate Wet
0.9–0.95	Severe Wet
0.95–0.98	Extreme Wet
>0.98	Exceptional Wet

Table 3
The average variability (%) explained by the first principal component for each month in this study in comparison to others. The average value was derived by averaging the gridded values over all of Australia.

Month	This study	Bayissa et al. (2019)
Jan	64	51
Feb	64	50
Mar	66	60
Apr	64	58
May	59	53
Jun	59	49
Jul	60	47
Aug	57	47
Sep	62	46
Oct	65	48
Nov	63	54
Dec	64	52

3.4. *Ground truthing and validation of the CDI*

The Drought Monitor relies on field observations from producers, extension officers, Climate Mates and local experts to provide feedback to "ground truth" observational data and corresponding indices. This is done through a monthly Drought Condition & Impact Report web-based survey to report on drought-related conditions and impacts in Australia. Participants are asked a range of multiple-choice questions reporting on crop and livestock production during a particular period (e.g., 1 month, 12 months) and how well the Drought Monitor map reflect the conditions in the local area.

First, recipients were asked to estimate how wet or dry it was in their local area, according to the definitions provided in Table 1.

Recipients were then asked to estimate how well each of the maps

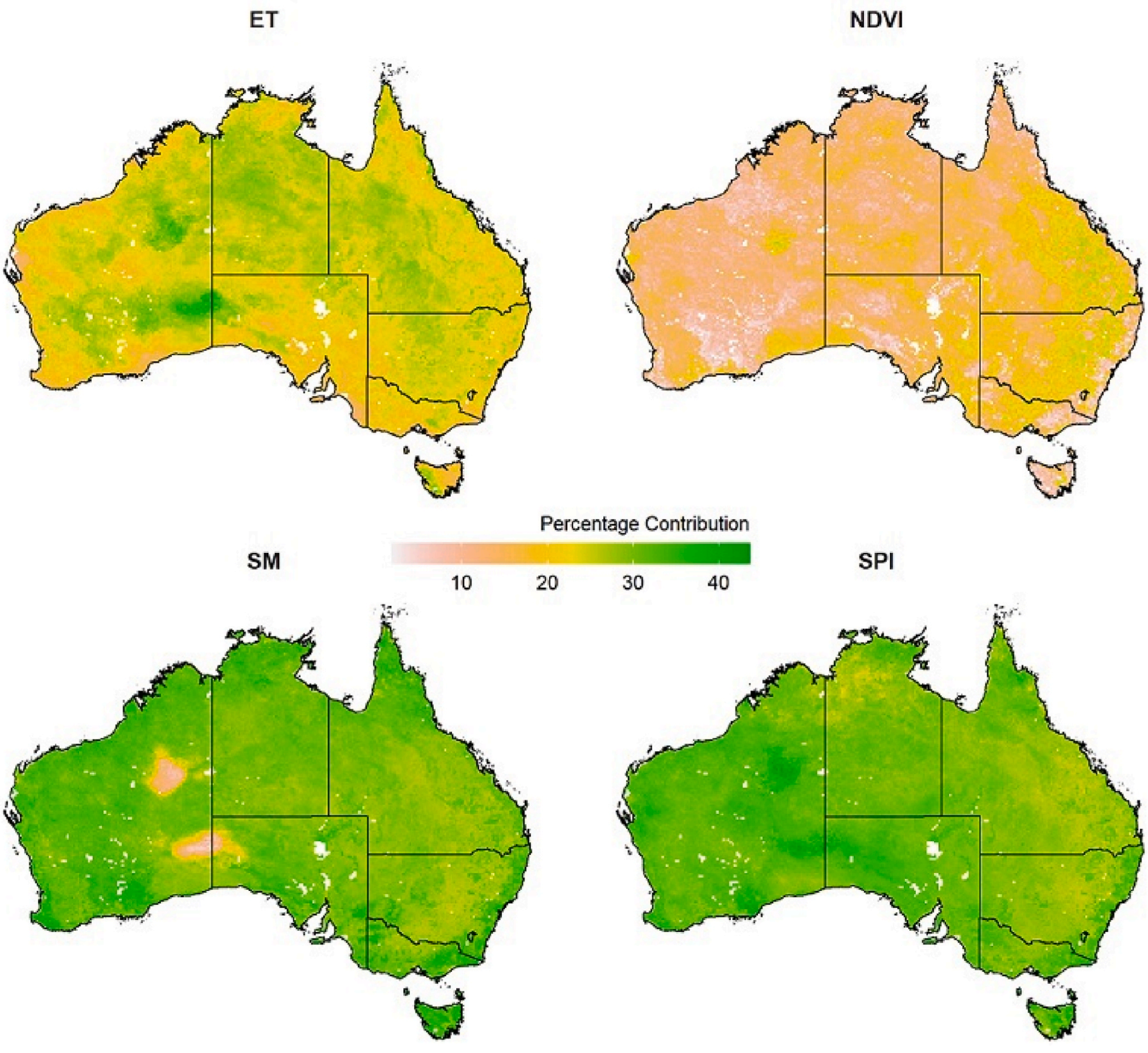

Fig. 3. Weights (percentage contributions) of each variable averaged over all months of the year used to develop the Australian Combined Drought Indicator (CDI).

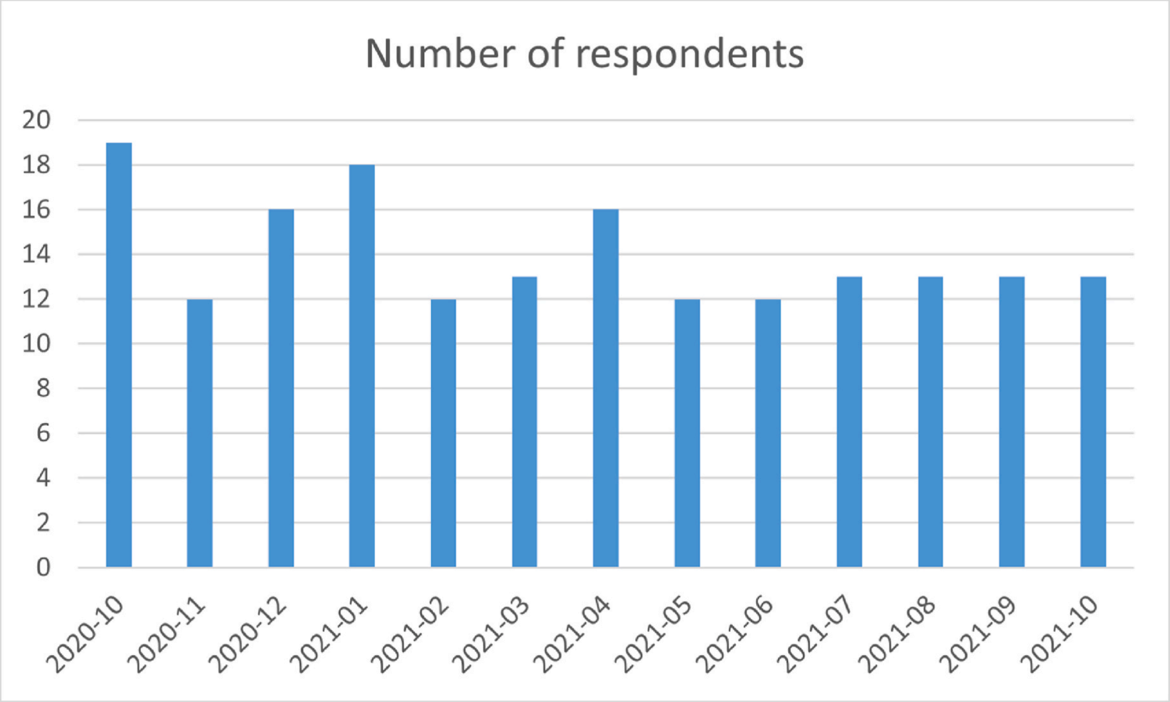

Fig. 4. Sample size of respondents over the course of the Drought Condition & Impact Report web survey.

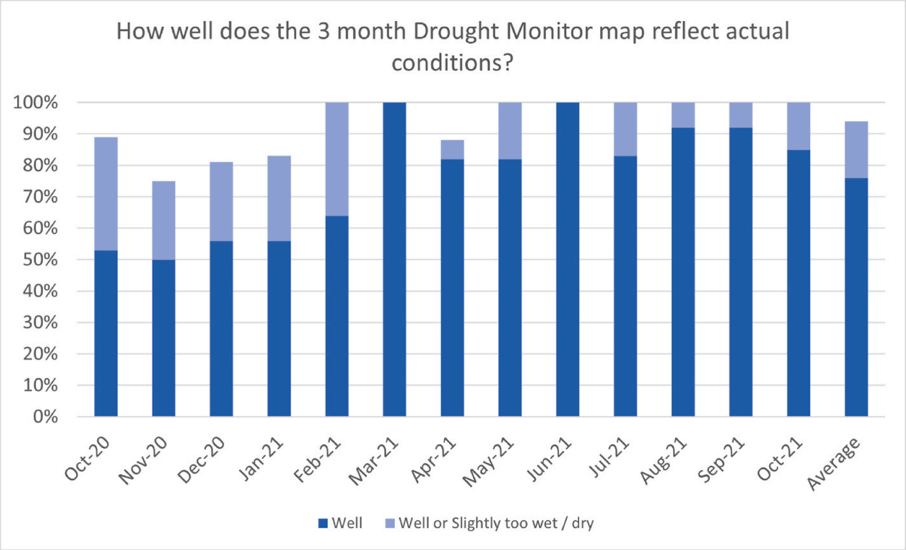

Fig. 5. How well does the 3 month Drought Monitor map reflect the actual conditions according to the Drought Condition & Impact Report web-based survey.

available reflected the actual conditions in their area. Possible answers were “way too wet”, “too wet”, “slightly too wet”, “well”, “slightly too dry”, “too dry”, and “way too dry”.

4. Results

4.1. A spatial representation of drought in Australia

The result of this study is a robust drought monitoring prototype tool, delivered online on the NACP project website as an easy to interpret, colour-coded series of maps (https://nacp.org.au/drought_monitor). The website provides a continuous delivery of regularly scheduled monthly updates as new meteorological data is made available by SILO, the Copernicus Global Land Service, and the BoM. With each monthly update, maps for each available time window are made available online. The CDI is customised for Australia’s unique and varied climate, using PCA to determine the optimal weighting between input variables based on the climatological history of each cell location. It is available at a spatial resolution of 0.05° (∼5 km) from April 1998 onwards. Samples of the Drought Monitor maps, produced April 2021, can be seen in Fig. 2. The categories for drought intensity were determined based on the US. Drought Monitor implementation (Svoboda et al., 2002). We defined a slightly dry period as conditions below the 30th percentile, a moderate drought as below the 20th percentile, a severe drought as below the 10th percentile, an extreme drought as below the 5th percentile, and an exceptional drought as below the 2nd percentile, as seen in Table 2.

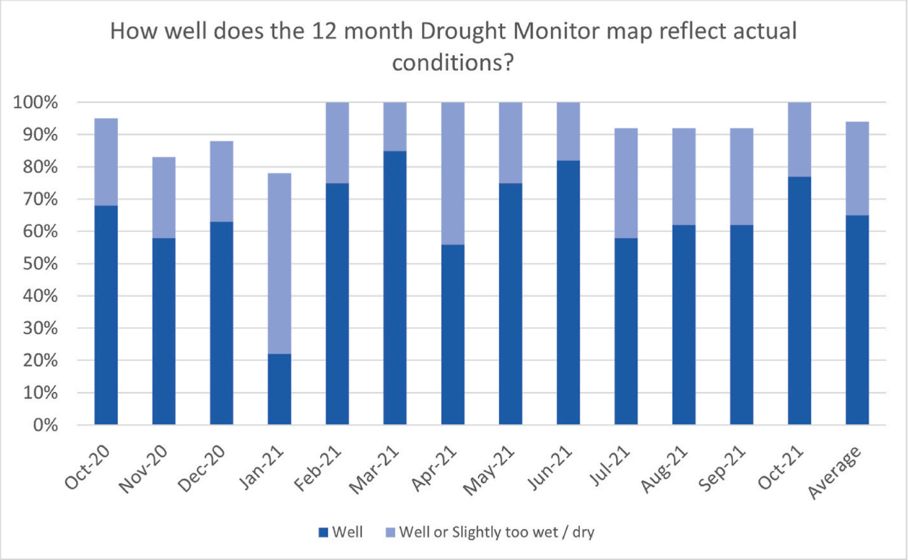

Fig. 6. How well does the 12 month Drought Monitor map reflect the actual conditions according to the Drought Condition & Impact Report web-based survey.

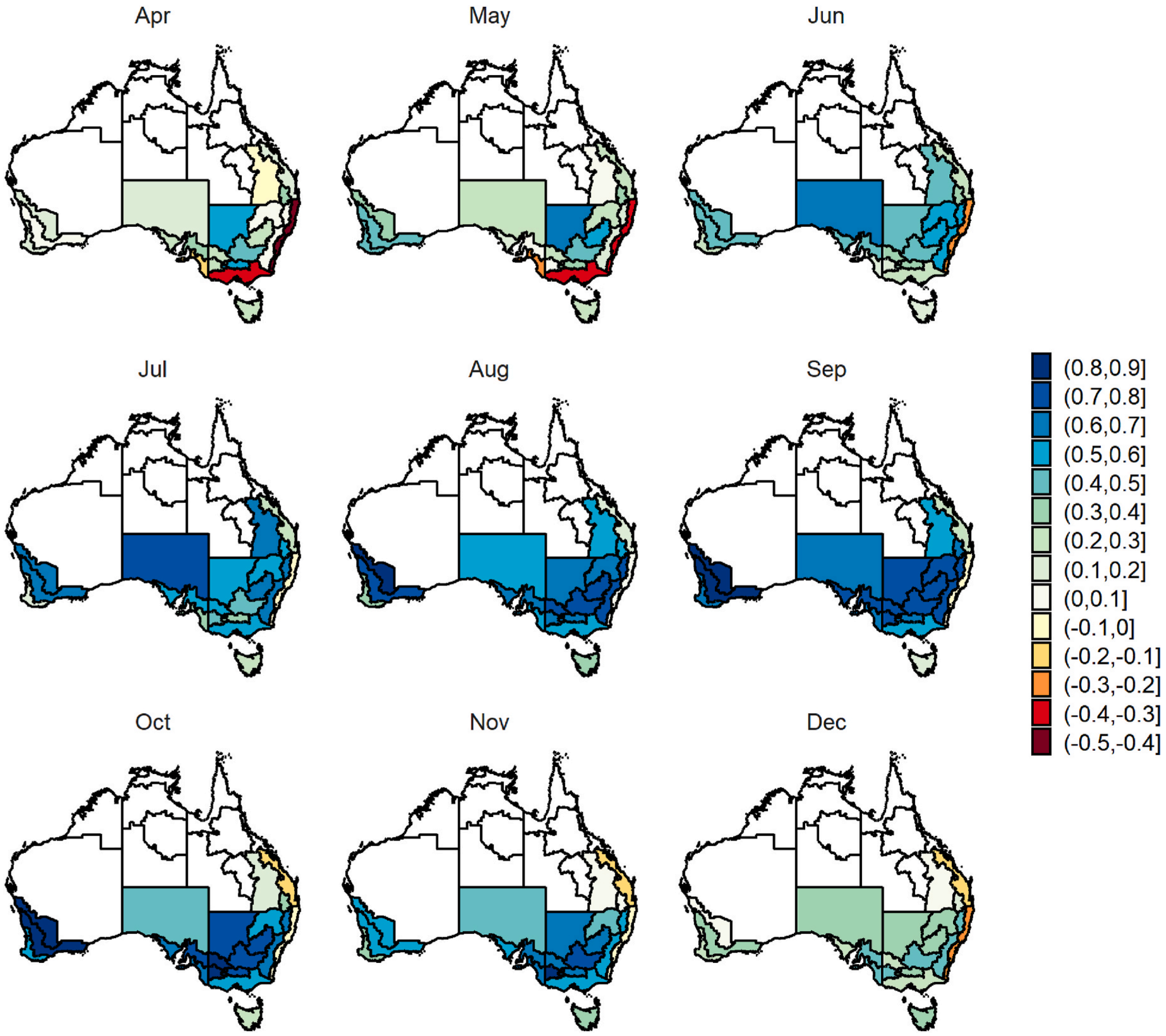

Fig. 7. Correlation coefficients between Australian Combined Drought Indicator (CDI) and detrended wheat yield over the period 1999–2020.

4.2. Contribution of input parameters

A total of 48 different sets of weights (percentage contributions) were computed, one for each month and each variable. This step was also repeated for all time windows, i.e., 3, 6, 9, 12, 24, and 36-month versions. Fig. 3 shows the spatial pattern of the weights (percentage contributions) of ET, NDVI, SM, and SPI variable averaged over all months of the year for the period 1998–2020 across Australia. Generally, the averaged percentage contributions of SM and SPI to CDI are larger than those of ET and NDVI. The averaged percentage contributions of NDVI, compared to other areas, is considerably higher along the east and southeast areas where the main cereal crops are grown. The results show that though the weights vary from month to month, variables contributing to the CDI most are SM and SPI (28–34%), followed by ET (20–27%) and NDVI (12–20%).

The variance of the input data explained by the first PC averaged over the entire Australia is presented in Table 3. The highest variance is shown in March (66%) and the lowest variance is observed in August (57%). The values of the variance obtained in this study were comparable with the result reported in the previous studies by (Barua et al., 2009; Bayissa et al., 2019; J. A. Keyantash and Dracup, 2004).

4.3. Evaluation of the CDI

4.3.1. Ground truthing via the Drought Condition & Impact Report web survey

The accuracy of the Australian CDI is evaluated through monthly web-based surveys with the support of producers, extension officers, Climate Mates and local experts. During the survey period, recipients were surveyed on their perceived accuracy of the 3-month and 12-month CDI maps for 13 months. Over the course of the survey, there were between 11 and 19 respondents each month, as shown in Fig. 4. The results indicate that for the 3-month CDI, respondents indicated that the Drought Monitor was correct (answered “Well”) 76% of the time, or close (answered “Well”, “Slightly too wet”, or “Slightly too dry”) 94% of the time (Fig. 5). For the 12-month CDI, respondents indicated that the Drought Monitor was correct (answered “Well”) 65% of the time, or close (answered “Well”, “Slightly too wet”, or “Slightly too dry”) 94% of the time (Fig. 6).

4.3.2. Evaluation against ABARES wheat crop yield data

Wheat is the major winter crop in Australia with planting generally starting in autumn (Apr–May) and harvesting, depending on seasonal conditions, occurring in spring and summer (Oct–Jan). The wheat yield (t/ha) data was linearly detrended to ignore the impact of other factors such as fertiliser and technology improvement. The linear detrend was performed using the detrend function in R, which computes the least-squares fit of a straight line and subtracts the resulting function from the data. Monthly CDI (Apr, 1998–Dec 2019) data, extracted and averaged over the cropping areas (as shown in Fig. 7), were used to quantify the correlation with the detrended wheat yield (1998/99–2019/20). It is also noted that, because of data availability, only regions with at least 10 data points were selected for the calculation.

The results of correlation coefficients for each month from Apr to Dec across broadacre regions are represented in Table 6. In general, a significant (at the level of 0.05) correlation between CDI and wheat yield are found during the mid-season (i.e., growth and development season) from Jul to Nov (IPAD). The positive correlation coefficients imply that wheat crop has higher yield in wetter conditions, which is expected. Generally, the CDI has significant correlation with wheat yield in inland regions, with less correlation in coastal regions and Tasmania. The pattern of correlation coefficients across broadacre regions for each month are mapped in Fig. 7. The impact of data length on the correlation calculation is also investigated using a leave-one-out cross-validation method (Fig. S1). It can be seen in Fig. S1 that the correlation coefficients of NSW Coastal, which has fewer data points, has a higher variability among correlation coefficients indicated by larger of quartile ranges, whiskers and outliers.

4.3.3. Evaluation against the AussieGRASS model

This study examines the relationship between the CDI and simulated pasture growth data. CDI data over Jan 1999–Dec 2019 were correlated with monthly total pasture growth simulated from the AussieGRASS model, on both seasonal and annual timescales. Only gridded cells with at least 10 data points were used for the calculation. The results reveal significant positive correlation between the CDI and total pasture growth, as shown in Figs. 8 and 9. While there was significant positive correlation for large areas of Australia, correlation varies across the country depending on time and location. For the seasonal analysis in Fig. 8, summer and autumn showed negative correlation in the Top End of the Northern Territory and northern Kimberley and little to no

Table 6

Correlation coefficients between Australian Combined Drought Indicator (CDI) and detrended wheat yield (t/ha) over the period 1998–2020. Bold values are significant at the level of 0.05. The numbers in the bracket are the number of years that the data is available.

Name	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
NSW Central West (22)	0.29	**0.54**	**0.55**	**0.61**	**0.76**	**0.79**	**0.74**	**0.68**	0.39
NSW Coastal (14)	−0.46	−0.39	−0.22	−0.01	0.06	−0.02	−0.08	−0.07	−0.29
NSW Far West (22)	**0.51**	**0.60**	**0.46**	**0.53**	**0.67**	**0.71**	**0.73**	**0.64**	0.37
NSW North West Slopes and Plains (22)	0.09	0.28	**0.52**	**0.57**	**0.64**	**0.79**	**0.57**	**0.42**	0.35
NSW Riverina (22)	**0.45**	**0.48**	**0.46**	**0.49**	**0.71**	**0.73**	**0.77**	**0.74**	**0.44**
NSW Tablelands (22)	0.08	0.19	**0.50**	**0.66**	**0.75**	**0.72**	**0.66**	**0.57**	**0.44**
QLD Eastern Darling Downs (22)	0.33	0.40	0.38	**0.54**	**0.58**	**0.65**	0.37	0.08	0.12
QLD Southern Coastal - Curtis to Moreton (22)	0.12	0.23	0.30	0.25	0.19	0.27	−0.15	−0.16	−0.10
QLD Western Downs and Central Highlands (22)	−0.04	0.07	**0.48**	**0.63**	**0.52**	**0.55**	0.19	0.09	0.07
SA Murray Lands and Yorke Peninsula (22)	0.32	0.06	**0.43**	**0.51**	**0.66**	**0.76**	**0.74**	**0.64**	**0.44**
SA Northern Pastoral (22)	0.19	0.28	**0.63**	**0.74**	**0.54**	**0.67**	**0.49**	**0.43**	0.36
SA South East (22)	−0.11	−0.25	0.15	0.35	**0.50**	**0.65**	**0.66**	**0.63**	**0.43**
TAS Tasmania (22)	0.24	0.27	0.17	0.26	0.35	0.16	0.27	0.32	0.37
VIC Central North (22)	**0.51**	0.34	0.33	0.31	**0.60**	**0.67**	**0.76**	**0.62**	0.39
VIC Mallee (22)	0.24	0.23	0.34	**0.52**	**0.74**	**0.74**	**0.81**	**0.67**	0.28
VIC Southern and Eastern Victoria (22)	−0.37	−0.37	0.29	**0.55**	**0.56**	**0.51**	**0.53**	**0.54**	0.28
VIC Wimmera (22)	0.20	0.01	0.20	**0.45**	**0.70**	**0.79**	**0.84**	**0.84**	**0.47**
WA Central and Southern Wheat Belt (22)	0.10	**0.44**	**0.48**	**0.61**	**0.78**	**0.86**	**0.87**	**0.55**	0.31
WA South West Coastal (22)	0.19	**0.46**	0.22	0.15	0.37	**0.61**	**0.58**	0.35	0.25

correlation on the south-east coast. For the annual analysis in Fig. 9, correlation was again weaker in the top end of the Northern Territory and along the east coast. In all analyses, the Tasmanian region performed poorly.

4.4. Evaluation against DPI combined drought indicator for NSW

The percentage of area in NSW in drought according to the DPI Combined Drought Indicator for NSW was compared against the Australian CDI for the same area. The categories provided by the NSW CDI is provided in Table 7.

For the purpose of this comparison, an area was considered to be in drought according to the NSW CDI if it fell under “Intense Drought” or “Drought”, but not under any other category. The reason that “Drought Affected (intensifying or weakening)” were not included was that the technical definition of a Drought Affected area was an area where at least one indicator was below the 30th percentile. In contrast, the Australian CDI considers an area to be in drought if the value of the CDI (a weighted average of all inputs) was below the 20th percentile, which is a more strict definition. Fig. 10 shows a comparative analysis between the NSW CDI and the Australian CDI-12 for a sample period (2016–2021, as available in the NSW CDI archive).

5. Discussion

The Australian Drought Monitor has the potential to become a highly valuable tool for agricultural producers and drought-declaration activities alike. It is the first product available to Australia to provide a snapshot of current drought conditions with complete continental coverage. By condensing multiple climate variables into one colour-coded map, it is particularly well suited to delivering drought updates to members of the public who may not have extensive climate knowledge. As it is available at a spatial resolution of 0.05° (~5 km), it has good coverage of rural areas that may be a significant distance from their nearest weather station. Results are timely, with conditions being updated by the 3rd of each month.

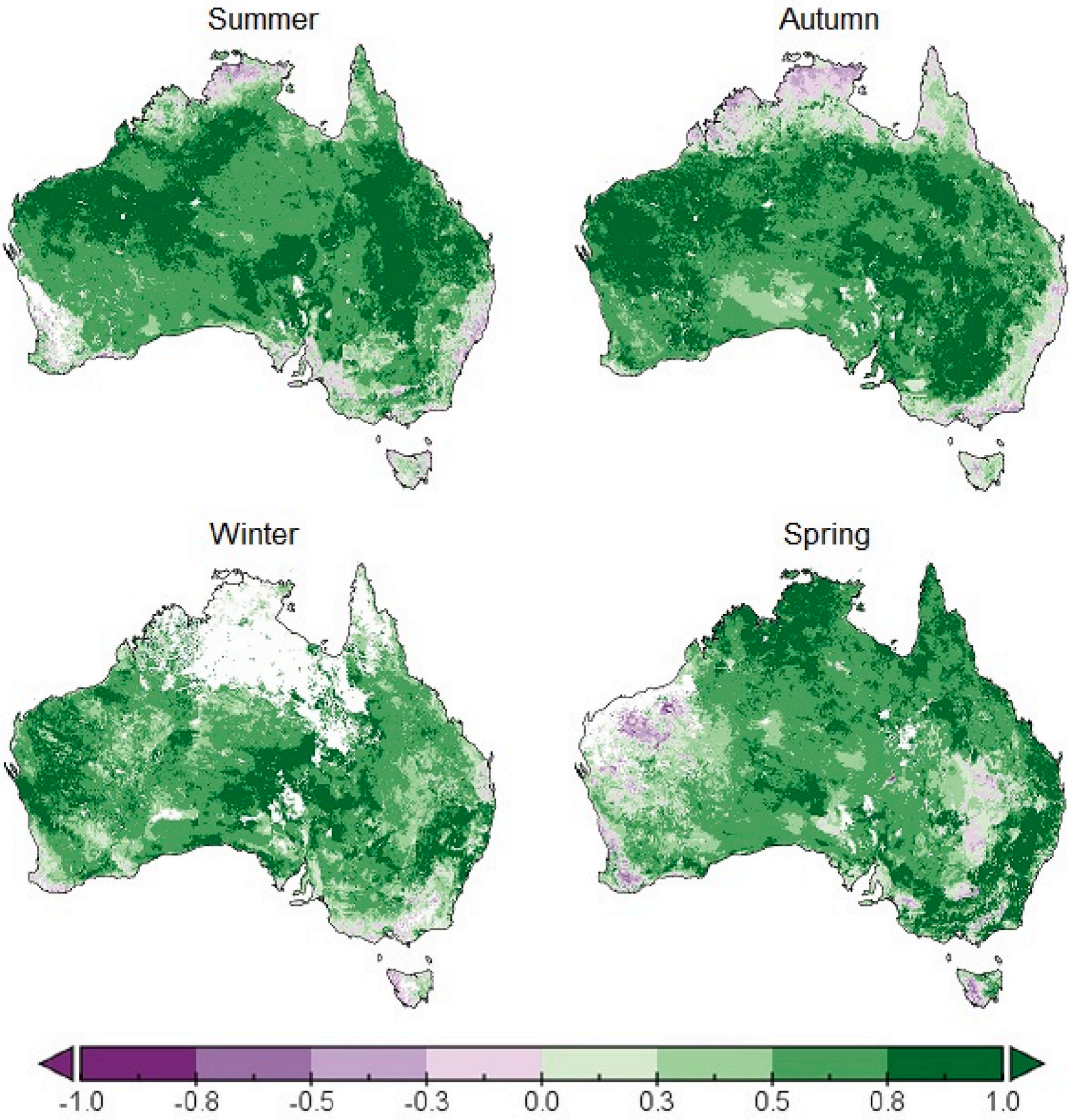

Fig. 8. Correlation coefficients between 3-month Australian Combined Drought Indicator (CDI-3) and 3-month total pasture growth (kg DM/ha) over the period 1999–2019.

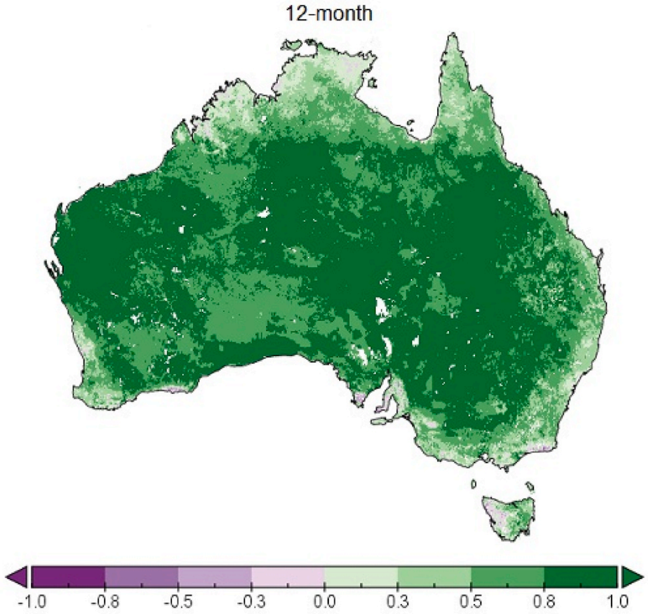

Fig. 9. Correlation coefficient between 12-month Australian Combined Drought Indicator (CDI-12) and 12-month total pasture growth (kg DM/ha) over the period 1999–2019.

5.1. The drought monitor in use

The tool is already in use by key decision-makers – official Drought Declarations for Queensland, available on LongPaddock's website (LongPaddock, 2021b), is used to inform the Drought Relief Assistance Scheme (DRAS) and impacts whether property owners in the region can apply for Queensland Government drought assistance. In May 2021, the Local Drought Committees (LDCs) responsible for official Drought Declarations in Queensland included the Australian Drought Monitor in the decision-making process for the first time, justifying the removal of drought status in five local government areas and the continuation of drought status in many other regions, reducing the overall drought-declared area of Queensland from 67.4% to 65% (Drought and Climate Adaptation Program, 2021). Fig. 11 shows a comparative analysis of drought between Queensland declarations and the CDI. This demonstrates that official drought declarations in Queensland corresponded with significant drought conditions as indicated by the CDI. The CDI generally responded more rapidly to changes in drought condition than official declarations, in both drought onset and recovery, which is supporting evidence that the CDI is an appropriate tool to inform drought declaration.

5.2. Evaluation results

Survey responses comparing the Australian Drought Monitor to field observations were moderately positive, with respondents indicating that the Drought Monitor represented real conditions "Well" approximately

Table 7
Categories of the DPI combined drought indicator for NSW (Department of Primary Industries, 2023b).

Category	Technical definition	Description
Intense Drought	All three indicators (rainfall, soil water, plant growth) are below the 5th percentile	Ground cover is very low, soil moisture stores are exhausted and rainfall has been minimal over the past 6–12 months.
Drought	At least one indicator is below the 5th percentile	Conditions may be very dry, or agronomic production is tight (low soil moisture or plant growth). It is possible to be in Drought when there has been some modest growth, or a few falls of rain.
Drought Affected (intensifying)	At least one indicator is below the 30th percentile and the rainfall trend is negative over the past 90 days.	Conditions are deteriorating; production is beginning to get tighter. Ground cover may be modest, but growth is moderate to low for the time of year. When indicators are close to the Drought threshold drought conditions are severe.
Drought Affected (weakening)	At least one indicator is below the 30th percentile and the rainfall trend is positive over the past 90 days.	Production conditions are getting tighter, but there have been some falls of rain over the past month. It is rare to enter the Recovering phase from the Non-Drought category; Usually there is a quick (1–2 week) transition into Drought Affected or Drought. When indicators are close to the Drought threshold drought conditions are severe.
Recovering	All indicators are below the 50th percentile but above the 30th percentile	Production is occurring but would be considered 'below average'. Full production recovery may not have occurred if this area has experienced drought conditions over the past six months.
Non-drought	At least one indicator is above the 50th percentile.	Production is not limited by climatic conditions.

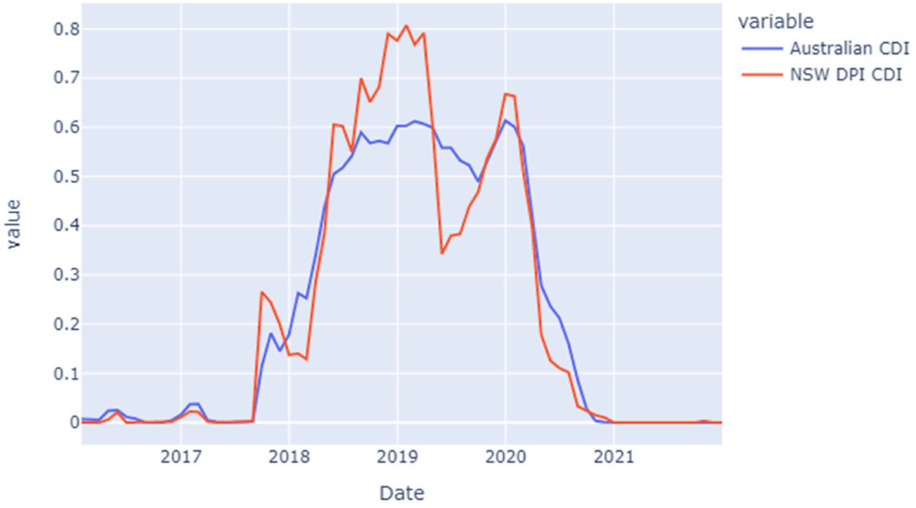

Fig. 10. Comparative analysis of drought between the DPI CDI for NSW and the developed Australian Combined Drought Indicator (CDI-12).

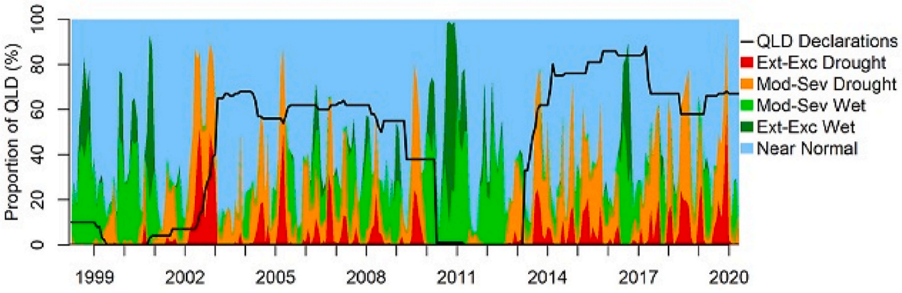

Fig. 11. Comparative analysis of drought between Queensland declarations and the developed Australian Combined Drought Indicator (CDI).

76% of the time for the 3-month map, and 65% of the time for the 12-month map. Ground truthing via human observation can be vulnerable to subjectivity. With respondents asked to compare their current drought conditions to one of eleven possible categories, a high level of precision in responses cannot be expected, particularly when considering that interpretations of how these categories relate to real-world conditions can vary from person to person.

However, survey responses are highly valuable for identifying situations where estimated conditions differ significantly from real-world conditions. It is much easier for respondents to flag issues if, for example, the product claims there is a severe drought but conditions are actually quite favourable. When examining responses rates of respondents indicating that the Drought Monitor was close to real-world conditions (defined as answers that are “Well”, “Slightly too wet”, or “Slightly too dry” but not any differences that are greater than this), it was found that respondents felt the Drought Monitor was close to real-world conditions 94% of the time for both maps. This demonstrates that cases of the Drought Monitor differing significantly from real-world conditions is highly rare according to survey responses, and is evidence of its accuracy as a product.

Correlation between the CDI and historical wheat yield was strongest in inland agricultural regions where the bulk of Australia’s wheat is grown (Fig. 7). The CDI showed less promise as a predictor of wheat yield in coastal regions, such as NSW Coastal, QLD Southern Coastal, Tasmania, and WA South West Coastal, however this may be due to much lower wheat production in these areas. Additionally, results in the NSW Coastal region may have been affected by fewer data points as demonstrated by a higher variability in leave-one-out cross-validated correlation coefficients (Fig. S1) for that region.

Comparison between the CDI and total pasture growth as simulated by the AussieGRASS model reveals a significant positive correlation overall. Poor results may appear in temperate regions in southeast Australia and improved pasture systems due to the design of the AussieGRASS model focused on tropical native pastures in Queensland (Carter et al., 2000). Additionally, the AussieGRASS model is considered to be more accurate in dry conditions than in wet conditions (DSITI, 2015). Negative correlation in the Top End of the Northern Territory and northern Kimberley (summer and autumn), and Tasmania could be due to high average rainfall in these regions during these periods resulting in lower skill (Fig. S2 in the Appendix).

As seen in Fig. 10, when compared against the NSW CDI, both indicators responded quickly to the onset and resolution of drought events. However, during the large drought event shown, there is some disagreement on the extent and severity of the drought. This could possibly be due to the varied technical definitions of drought between the two indicators, however, there is still strong resemblance.

5.3. *Limitations of the tool*

While the Drought Monitor can provide a vital drought monitoring service to the decision-makers of Australia, there are some limitations associated with the product and avenues of investigation for further improvement.

It should be noted that the purpose of including principal component analysis (PCA) in this work is to calibrate the weightings of inputs in a way that captures the maximum variance of the four variables, which is not necessarily calibrating the weightings of inputs for drought. Because there is no comparison against a response variable that measures drought, this is an unsupervised approach.

The Drought Monitor offers full continental coverage of Australia at a high spatial resolution, however its reliance on interpolated grid data may affect its accuracy in rural Australia where there is a lower density of data collection points. This issue is somewhat mitigated by the inclusion of NDVI data, which is remotely sensed via satellite at a high spatial resolution. However, rainfall and evapotranspiration data are collected from SILO, which uses mathematical interpolation techniques to construct spatial grids based on observational records. Rainfall is generally considered difficult to interpolate because it is less stable over significant distances than other variables such as temperature. Soil moisture data, collected from the Australian Landscape Water Balance model (AWRA-L v6), also relies on gridded rainfall and temperature data that is interpolated from station records (Viney et al., 2015). This issue may be addressed in future development by transitioning fully to high-resolution remotely-sensed data. However, soil moisture data is still vulnerable to bias due to variation in soil textures across Australia and this should be examined in the future.

The Drought Monitor offers snapshots of drought across the continent at seven different time windows – 1, 3, 6, 9, 12, 24, and 36 months. The inclusion of multiple time windows is appropriate due to the inherent complexity of drought and the myriad ways that drought impacts can manifest. Short-term rainfall deficiency, as captured in the 1-month CDI, can lead to short-term soil moisture and crop stress known as a meteorological drought, especially if it occurs during the growing period. As drought conditions persist into 3–9 months, it can progress into an agricultural drought, causing possible crop failure and lost income. Over a 12-month period, a hydrological drought begins to impact the water supply. Droughts that persist longer than this can also have significant socio-economic impacts include job losses, business closures and increased need for mental health services.

However, more time windows do not necessarily contribute to a better product. By having many options available on the Drought Monitor, a responsibility and expectation has been placed on its users to be able to accurately consider multiple maps and identify which of them is most relevant to their situation. Such an expectation may be unrealistic and lead to “analysis paralysis” among users. Users may mislead themselves by choosing the map with the most favourable drought conditions for their region, but not necessarily the highest relevance to their situation. Users may also be motivated to access other resources that are more simplified. The Drought Monitor should be able to represent the inherent complexity of drought but should also ensure brevity and clarity to prevent these issues from arising. The U.S. Drought Monitor balances these needs by featuring only a single map, while marking certain areas with the letters “S” and “L”, indicating short and long-term impacts respectively.

5.4. Future development

In future iterations, the Drought Monitor may be simplified and time windows condensed down to three options, representing short, medium and long-term impacts. Continued feedback from users who rely on this product will be crucial for determining which of the timescales currently available have the highest value and should be retained in the future.

The Drought Monitor is a relatively new tool that is still under assessment by Climate Mates, Extension Officers, and producers who are associated with the Northern Australia Climate Program (NACP). As users provide feedback on its capacity to accurately represent on-ground conditions, the Drought Monitor is subject to future development and refinement and may be fully released in the coming months.

6. Conclusion

This study introduced the Australian Drought Monitor (https://nacp.org.au/drought_monitor) as a novel and robust drought monitoring tool which is specifically calibrated for accuracy within Australia. The Australian Combined Drought Indicator (CDI), which is at the core of the Drought Monitor, was examined alongside agricultural observations such as wheat yield, and the simulated agricultural model AussieGRASS, and was found to have significant correlation. Survey responses by users were also positive, with respondents indicating that they rarely felt that the product was significantly inaccurate based on conditions in their region.

There are avenues for potential future development, such as revisiting the selection of input data as more remotely-sensed options become available in Australia, which will increase the accuracy of the Drought Monitor in rural areas where weather stations are sparse. Users may be consulted in the future on the topic of condensing the many time scales available into fewer, more relevant options.

The Drought Monitor is currently in use by official Queensland Drought Declarations, and is well-positioned to inform drought declaration decisions in other regions of Australia. It has the potential to become a valuable tool and well-known tool for identification of drought conditions across Australia, with a potential impact similar to the U.S. Drought Monitor, by which this product was inspired.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Laura Guillory reports financial support was provided by Meat and Livestock Australia. David Cobon reports financial support was provided by Meat and Livestock Australia. Thong Nguyen-Huy reports financial support was provided by Meat and Livestock Australia. Christa Pudmenzky reports financial support was provided by Meat and Livestock Australia. Roger Stone reports financial support was provided by Meat and Livestock Australia.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2023.105852.

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