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Research Article

Climate Services for Agriculture: Tools for Informing Decisions Relating to Climate Change and Climate Variability in the Wine Industry

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Background and Aims. Australia's changing climate is already impacting the agriculture sector and will continue to do so in the future. To help respond to these impacts, the Climate Services for Agriculture (CSA) platform presents readily accessible climate data, including future climate projections, relevant to specific agricultural commodities. This wine industry example aims to demonstrate the functionality and utility of the CSA for national use across a broad range of commodities. *Methods and Results*. The platform includes commodity-relevant climate indices designed in consultation with experts to ensure that they are as salient to producers as possible; the wine-grape specific indices include measures of growing season temperature, rainfall, extreme heat, and frost. Here, we describe the research behind the wine-grape specific indices and present sample outputs from the CSA platform for a site within a selected winegrowing region. We note the CSA platform has been developed through an extensive and continuing user engagement initiative, ensuring it meets the needs of the agriculture community as they grapple with how to make decisions based on longer term climate projections. *Conclusions*. Provision of past, seasonal outlook, and future climate information for Australia and for a range of important agricultural commodities can help improve on-farm planning and decision-making to respond to climate risks. The wine industry provides a leading example of how to use these data for decision-making, noting ongoing adjustments will be needed. *Significance of the Study*. The CSA platform brings together historical climate data, seasonal climate outlooks, and future climate projections to assist agricultural producers to better manage climate variability and climate change. It aims to nationalise this information for all major agricultural commodities in Australia. We use wine production as a demonstration case here.

1. Introduction

Human-induced climate change is already affecting weather and climate extremes in every region across the globe. Evidence of observed changes in climate extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, has strengthened over recent years [1–3], as has attribution to human influence [4].

Sectors such as agriculture, which are exposed to climatic variability and change, will become increasingly more impacted as the climate continues to change [5]. The wine industry, like other agricultural industries, will need to continue to manage the effects of the changing climate. The industry will need to identify opportunities and respond to threats that these changes will bring, both now and in the coming decades, to continue to be successful [6]. Evidence of wine-grape sensitivity to climate has already been observed in Australia with shifts toward earlier harvest dates [7, 8] attributed in part to increased growing season temperatures and changes to water availability [9]. This shift in harvest timing can impact profitability by affecting wine quality [10] and increasing complexity in wine-grape harvest logistics [11].

Climate data and information can assist wine-grape growers and the agriculture sector more broadly to adapt to climate change (e.g., [12, 13]) but information needs to be contextualised and tailored in order to facilitate decision-making [13], including for Australia's wine industry [14]. The Climate Services for Agriculture (CSA) platform, developed by the Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) with funding through the Australian Government's Future Drought Fund [15], aims to build the resilience of Australian agriculture to climate change and variability by providing access to tailored and targeted climate information. The CSA methodology features a codesign approach [16], which involves significant user engagement.

Innovation of the CSA platform lies in the nationally scoped historical, seasonal forecast, and future projection climate information provided in one place, with data available for "point-and-click" locations across Australia. A key feature of the tool is the agriculturally relevant climate indices, which have been tailored specifically for major Australian commodities, drawing on the scientific literature, with guidance from producers and other commodity experts. This combination of national scope and multi-industry application makes the CSA platform unique. The platform is designed to allow farmers to access climate risk knowledge across multiple commodities if required. Historically, research in this area has tended to be subnational in focus and for singular commodities [17].

For the wine industry, an improved understanding of historical, current, and future growing season temperatures at any given site can assist with targeting the most suitable selection of grape varieties and/or wine styles to best align with climate conditions [11]. Related to the warming climate are changes to rainfall which will also have implications for wine-grape production (e.g., quality), and as described by Essling [18], irrigation access and disease pressure. As projected changes to rainfall are not uniform across wine-growing regions, or across the seasons [19], the CSA platform can be employed to better understand how these future conditions may unfold in different regions, especially as climate change may alter the range of historic experience.

Here, we will describe the development of the CSA platform, including how a codesign process has directly influenced the features presented on the platform. We will also discuss the climate risk indices that have been included that specifically relate to wine production and provide an example of the use of the platform for a winegrowing region. This example aims to demonstrate the functionality and utility of the CSA platform for the wine industry.

2. Materials and Methods

2.1. Codesign (User-Centric) Approach. In order to develop a platform that is relevant and provides value to users, it is important to use codesign. In this context, we use the codesign term to describe the process of engaging with users to design and develop features of the CSA platform. This engagement is ongoing and ranges from individual face-to-face interviews to test and showcase the platform at industry gatherings. We provide examples of how user engagement has directly influenced the development of features of the platform below and has shaped what data are presented, and in what form. Engagement with the wine industry has been particularly informative, as wine producers are already thinking about a longer-term time horizon for climate change adaptation and mitigation.

Through employing a user-centric design approach, each successive release of the CSA platform is moving its focus from that of a climate data delivery tool to a focus on developing insights relating to adaptation outcomes. The goal is shifting from a focus on improving access to information, to improve how the information is used. This requires a novel approach to research that is flexible, transdisciplinary, and iterative (learning). The high-level roadmap (Figure 1) provides a timeline summary plan of how this will be progressed:

2.2. Wine Industry Climate Indices. The CSA team identified eight climate indices related to the wine industry (Table 1). The indices and their parameterisation are based on peer-reviewed literature, industry reports, domain expert interviews, and end-user feedback. The inclusion of indices was determined by the availability of climate data, limitations of the science relating to projections, project scope, and technical feasibility of data provision.

2.3. Growing Season Temperature Indices. Numerous temperature-based indices have been used to characterise suitable regions for different varieties and wine styles. These include mean growing season temperature (GST) [20–22], growing degree days (GDD) [22, 23], mean January temperature (MJT) [24–26], biologically effective growing degree days (BEDD) [27], and the Huglin heliothermal Index (HI) [28]. Of these, no single metric has been found to outperform all others across the range of decisions that these metrics are used to inform (e.g., matching variety to regions, predicting phenology). For CSA, in the interest of pragmatism, advice was sought during expert-interviews on narrowing the selection to the more commonly applied indices with mean growing season temperature, GDD, and mean January temperature being included. All growing season temperature metrics currently displayed on the platform were calculated for 1 October to 30 April, a common estimate of the growing season across all wine-grape regions in Australia [8, 10, 20–22, 29]. Future versions of the CSA platform will allow for some customisation of the

Figure 1: CSA focus transition from "data delivery" to "insights for adaptation."

indices, e.g., changing of temperature thresholds or growing season window to suit growers' specific requirements.

2.4. Extreme Heat Index. The impact of extreme temperatures on wine-grape production was demonstrated by the significant crop losses being recorded after the 2009 heatwave in southern Australia [30], which coincided with the veraison stage of the south-eastern Australian wine-grape crop. This was likely caused by the combination of a heatwave event in Australia's southeast in early 2009 and, in some areas, a lack of access to irrigation water [30, 31]. Extreme heat events can affect vines' production and quality across several different growth phases. Extreme temperatures reduce photosynthetic rates and increase transpiration, reducing productivity [32], affect fruit set, and cause berry shrivel [33] which reduces yield, and interfere with berry chemical composition [32].

The temperature thresholds for extreme heat in the context of viticulture have been defined differently in different studies with maximum temperature greater than 35°C, being common across these [21, 22, 30]. While extreme heat on a single day may cause damage, "heatwaves" defined as three or more consecutive days above 35°C, are more difficult to manage and tend to cause more damage than single day heat events. Using a heatwave definition also aligns with practical application, with Hayman et al. [33] noting that many viticulturists make vineyard management decisions based on heatwave definition of three or more consecutive days above 35°C or 40°C. As noted above, future versions of the CSA platform will allow for selectable options relating to thresholds to be adjusted to suit growers' specific requirements, noting extreme heat definitions vary depending on the region [30].

2.5. Frost Index. Incidences of frost across the wine-grape growing season can cause minor damage through to total crop loss. An example of a costly frost event occurred in November 2018 in Western Australia, where wine-grape growers reported 70 to 80% crop loss from a single event [34]. More severe frost events may also affect the production potential of the following season due to more significant damage to the vines [35].

To estimate potential frost risk, counts of days below a 2°C minimum temperature threshold [22, 36] are presented on the CSA platform. Under many conditions, a temperature of 2°C measured at the height of the Stevenson Screen thermometer (about 1.2 m above the ground) is approximately equivalent to a temperature of 0°C at ground level (e.g., [37]. The frost risk period defined by the CSA platform of 15 August to 30 November captures the likely frost risk period for sensitive growing tissues, is relevant across regions and varieties, and based on other definitions of frost sensitivity [21, 23, 36] and expert feedback.

2.6. Rainfall Indices. Total summer rainfall can be a guide for investigating potential changes to disease (bunch rot and Botrytis) and grape ripening conditions at harvest [18, 21, 38]. This index provides insights into potential trends in disease pressure and ripening conditions in the lead up to harvest. It does not predict actual disease incidence or severity which is dependent on the presence of the disease, other climate conditions (e.g., temperature and wind), and grower management prior to and during any outbreak. It does provide an indication of potential changes to risk in the future.

Rainfall received over the growing season can influence yield (particularly for nonirrigated vines) and minimise irrigation costs [38]. A study investigating inter- and intraregion *terrior* in Australia used growing season rainfall (1st October to 30th April), along with other indicators, to help differentiate regions [24]. Following these examples, we represent growing season rainfall as total rainfall received from 1st October to 30th April.

Nongrowing season rainfall (1st May to 30th September) [22], is important for two reasons. First, for vineyards with on-farm irrigation dams, nongrowing season rainfall contributes to replenishing dam levels. Second, low soil moisture levels at the beginning of the season can reduce shoot growth and, thus, canopy size, which reduces the ability of the vine to generate carbon resources to support berry growth [39, 40], potentially influencing yield.

2.7. Historical Climate Data. The daily historical rainfall and temperature data are from the Bureau of Meteorology's Australian Gridded Climate Data (AGCD) dataset [41, 42]. This nationally consistent, gridded dataset from which the CSA data are sourced starts in 1900 for rainfall and 1910 for temperature. The AGCD gridded data are produced by interpolating data from Bureau weather stations around Australia and presenting it on a uniform national 5 km grid. This dataset meets the CSA goal of national accessibility of climate risk information.

Table 1: Wine-grape indices codeveloped for the CSA platform.

Index name	Index equation
Growing season temperature (°C) (April to October)	$\sum_{1\ \mathrm{Oct}}^{30\ \mathrm{Apr}} T\mathrm{mean}$
Growing degree days (°C) (April to October)	$\sum_{1\ \mathrm{Oct}}^{30\ \mathrm{Apr}} \text{if } (T\mathrm{mean} > 10°\mathrm{C};\ (T\mathrm{mean} - 10))$ $\text{if } (T\mathrm{mean} \leq 10°\mathrm{C};\ 0)$
Mean January temperature (°C)	$\sum_{1\ \mathrm{Jan}}^{31\ \mathrm{Jan}} T\mathrm{mean}$
Extreme heat risk (heatwaves) (per year)	$\sum_{i=1\ \mathrm{July}}^{30\ \mathrm{June}} \text{if } (T\max_i \text{ and} T\max_{i+1} \text{and } T\max_{i+2} \geq 35°\mathrm{C};\ 1)$ $\text{if } (T\max_i \text{ or } T\max_{i+1} \text{or } T\max_{i+2} < 35°\mathrm{C};\ 0)$
Frost risk (days) (August to November)	$\sum_{15\ \mathrm{Aug}}^{30\ \mathrm{Nov}} \text{if } (T\min \leq 2°\mathrm{C}; 1)$ $\text{if } (T\min > 2°\mathrm{C}; 0)$
Summer rainfall (mm) (Dec to Feb)	$\sum_{1\ \mathrm{Dec}}^{28\ \mathrm{Feb}} \mathrm{Rainfall}$
Growing season rainfall (mm) (April to October)	$\sum_{1\ \mathrm{Oct}}^{30\ \mathrm{Apr}} \mathrm{Rainfall}$
Nongrowing season rainfall (mm) (May to September)	$\sum_{1\ \mathrm{May}}^{30\ \mathrm{Sept}} \mathrm{Rainfall}$

i = day of year. NB: daily Tmean, daily Tmax and daily Tmin are used in above formula.

2.8. Seasonal Rainfall Outlooks. In addition to climate change risk, CSA draws upon the Bureau of Meteorology official seasonal outlooks [43] to help growers manage current seasonal rainfall variability for the upcoming season. This information is presented as a probability (or chance) of rainfall exceeding a specific threshold (e.g., the chance of rainfall being above the median, expressed as a percentage). These are available for both seasonal and monthly timeframes. The forecast is updated weekly in line with the Bureau of Meteorology updates.

Different users relate differently to outlook information, particularly in relation to rainfall. Some users are interested in specific rainfall amounts (e.g., 200 mm for the season), while others make decisions at specific probabilities (e.g., if there is a 75% chance it will be drier than average). To meet these diverse needs, the CSA platform presents the spread of plausible rainfall amounts into rainfall scenarios that can be viewed in the following ways:

(i) Chance of at least: the chances that rainfall for the selected outlook period will exceed defined thresholds, e.g., chance of at least 200 mm over the coming three months, or 10 mm in a week.

(ii) Outlook scenarios: rainfall amounts that are likely at a particular percentage chance, e.g., 25% chance of receiving the given rainfall amount for the period.

(iii) Rainfall at your location for historical median, past year comparison, and recent period.

2.9. Climate Projections. The CSA platform has been built using both application-ready future climate data from the Climate Change in Australia (CCiA) set of national climate projections [19] and from the National Hydrological Projection dataset [44]. Here we specifically describe application-ready data from CCiA, from which we present rainfall and temperature variables. Data from this product is available at a daily time scale on a 5 km grid across Australia for three future timeframes centred around 2030 (2016–2045), 2050 (2036–2065), and 2070 (2056–2085). These data use information from the Coupled Model Intercomparison Project phase 5 (CMIP5) [45], which provide a repository of simulations from the international climate modelling groups. Specifically, the CCiA application-ready data incorporate projected climate changes simulated by a set of eight CMIP5 models selected to represent most of the range of projected change for Australia [19]. These data are well-established, well-documented, and have been thoroughly evaluated (e.g., see list of Technical Reports and peer-reviewed literature on https://www.climatechangeinaustralia.gov.au).

It is important to acknowledge that climate projections are derived from climate models that have limitations:

(i) Global climate models (GCMs) can provide useful climate projections over the next two decades and beyond at global and continental scales. However, uncertainties at regional and local scales over the next decade are strongly influenced by natural variability, which is hard to predict.

(ii) Global climate models (GCMs) have coarse resolution and cannot adequately represent weather-scale (1–10 km) phenomena, so downscaling methods have been used.

The "downscaling" method used to produce the application-ready data is a scaling method, whereby the changes projected by the global climate models (~200 km resolution) are applied to the historic observed gridded data (~5 km resolution). In this way, the climate and underlying weather conditions from the observational period are carried forward in a perturbed sense to represent plausible future conditions. The numerical precision of these data must not be confused with accuracy; the downscaled projections are plausible, rather than precise.

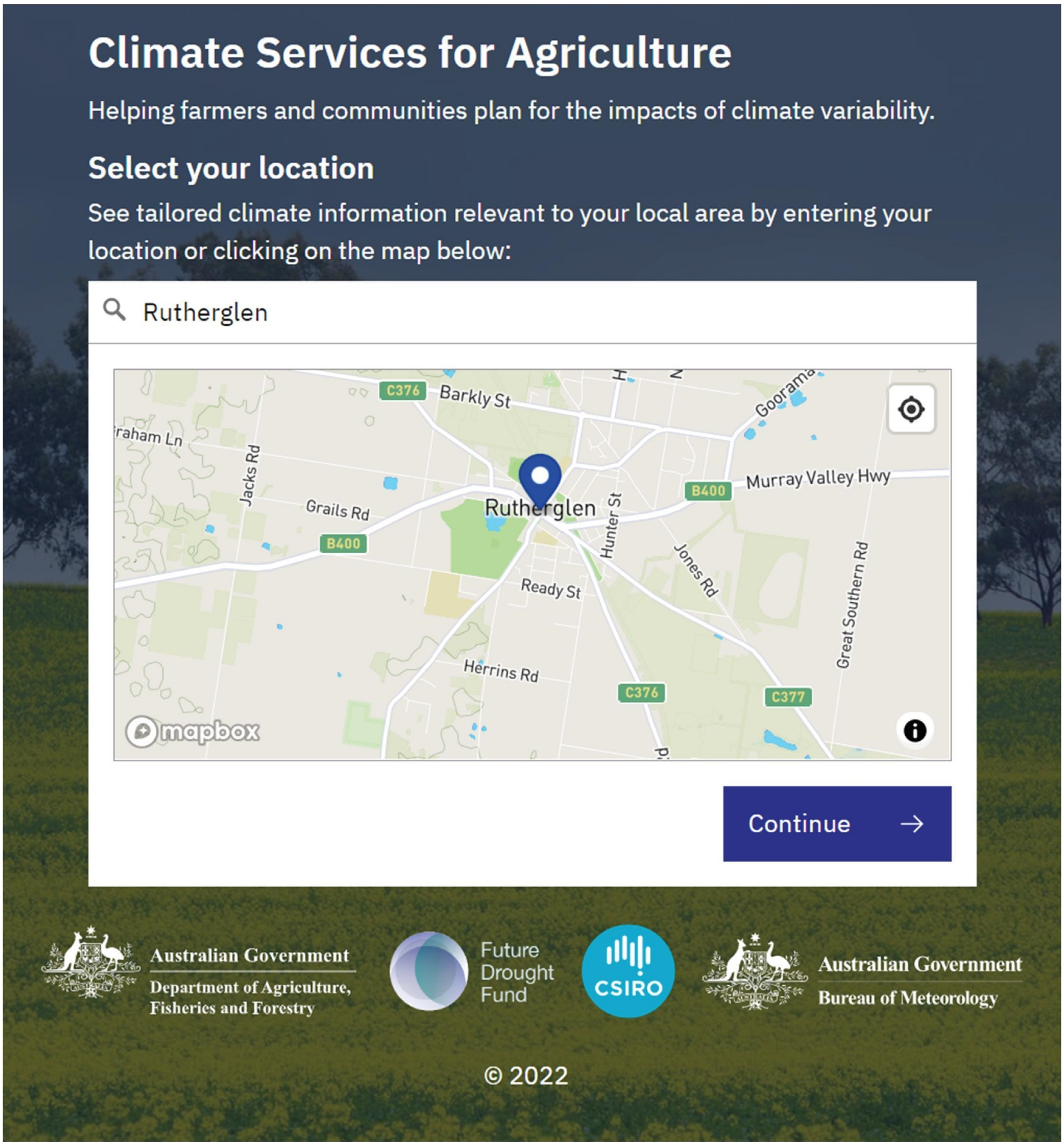
The CMIP5 repository includes model simulations of different "Representative Concentration Pathways" (RCPs) that describe how the energy imbalance of the climate system, or "radiative forcing" due to greenhouse gas emissions and other anthropogenic forcings may evolve [46]. It is desirable that a range of RCPs are used in climate risk assessments to assess different plausible future pathways for socio-economic change, technological change, energy generation, and land-use change and associated emissions and atmospheric concentrations of greenhouse gases and air pollutants. Two RCPs, RCP8.5 termed "high emissions" and RCP4.5 termed "medium emissions," are represented on the CSA platform [19].

The high, RCP8.5, pathway reflects a future in which little additional action on reducing greenhouse gas emissions is taken. Under this scenario global greenhouse gas emissions continue to increase significantly until near the end of the 21st century, and global warming relative to preindustrial times is very likely in the range of 3.3 to 5.7°C at the end of the century. RCP4.5 corresponds to a greenhouse gas emissions pathway that peaks in 2040 and then declines to 1960s emission levels by 2090 [4]. Under this scenario, the very likely range for global warming at the end of the century is 2.1 to 3.5°C, and the Paris Agreement global warming limit of 2°C is extremely likely to be exceeded [47].

3. Using the CSA Platform: Rutherglen Example

To demonstrate the functionality of the CSA platform, we use a site in the Rutherglen wine-growing region (Figure 2) as an example.

The platform presents two historical 30-year periods (Figure 3, top left). A 30-year period is deemed long enough to capture the year-to-year variability of the climate in the selected region but short enough for long-term climate trends not to be a dominant influence [48]. By comparing the recent period (1991–2020) to the past period (1961–1990), a user can determine if there have been any recorded changes in climate in their region over time. This also provides context for any projected climate changes in their region. For example, in the climate metric MJT (°C), there has been an observed increase in the average temperatures of 1.1°C from 1961 to 1990 (23.2°C) to 1991–2020 (24.3°C) in Rutherglen.



Climate Services for Agriculture

Helping farmers and communities plan for the impacts of climate variability.

Select your location

See tailored climate information relevant to your local area by entering your location or clicking on the map below:

Rutherglen

Figure 2: CSA interface indicating how a user selected their location (https://climateservicesforag.indraweb.io/).

Future projections are shown under two emission scenarios (RCP4.5 and RCP8.5), as well as the past observations split into two periods (Figure 3, bottom left). For the projections, the distribution of the data are based on data from 8 GCMs. For each of those models, we have 30 years of data, and we can calculate an average across those 30 years for each model. This means we have a set of 8 model averages. The range across these, represented by the 10th and 90th percentile values, is shown as the inner, lighter shaded box (Figure 3). It is useful to think of these as describing the range of the average state of the climate. The thin horizontal bar shows the average of this set of values.

If we combine all the data from each of the 8 models, we can calculate the projected range of values. This is calculated as the 10th and 90th percentile across the full dataset (8 models × 30 years) and is presented as the outer, darker shaded box. It is useful to think of this as the range due to natural year-to-year variability. Incorporating year-to-year variability shows, for instance, that the coolest 10% of Januarys during 1991–2020 had MJT of 21.8°C or less, and the warmest 10% of Januarys had MJT of 26.5°C or greater (Figure 3, bottom left).

In the example shown, depending on the emission scenario, MJT might increase on average from 23.2°C

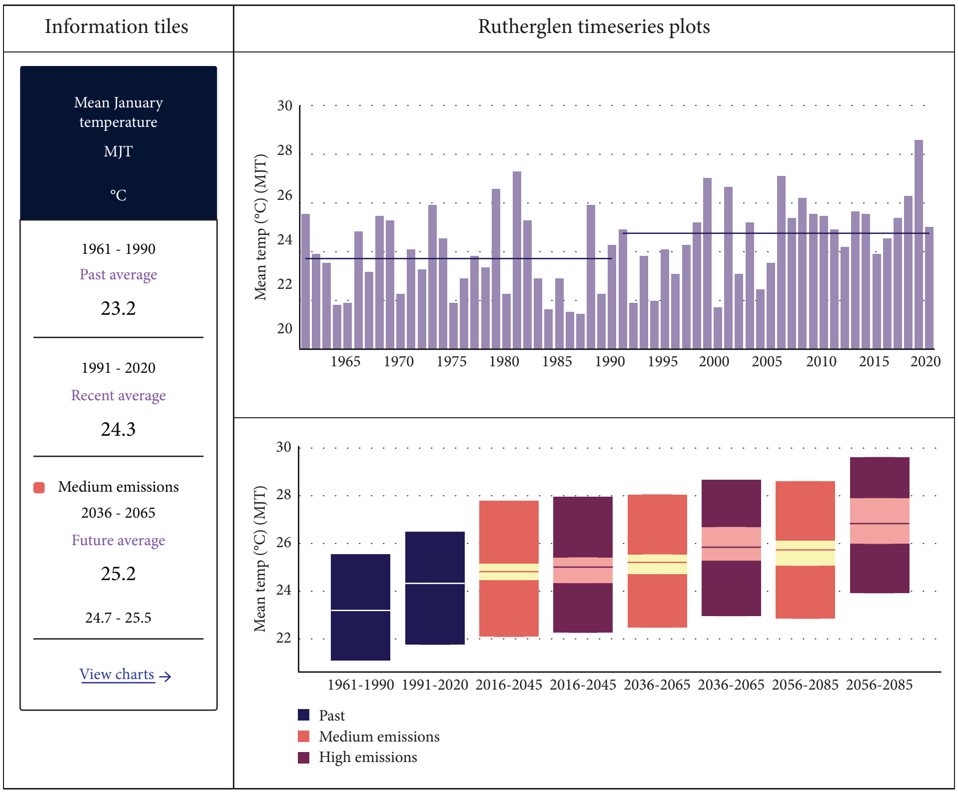


FIGURE 3: Mean January temperature (MJT) (°C) for Rutherglen for specified past and future periods summary (left). Past observations (1961–2020) split into two epochs (1961–1990) and (1991–2020) (epoch average denoted by the black horizontal line) (top right). Past (1961–1990; 1991–2020) (period average blue line, full dark blue bar including year to year variability) and projected 2030 (2016–2045), 2050 (2036–2065), and 2070 (2056–2085) period average and model average range (central lighter colour of the bar), and including variability (10th to 90th percentile indicated by the full extent of the bar) of MJT (°C) (medium emissions, RCP4.5; yellow/orange) and (high emissions, RCP 8.5; pink/purple) (bottom right). Data for past climate sourced from AGCD [41, 42] and future projections are from eight CMIP5 models.

(1961–1990) to 25.2°C (low emissions) or 25.8°C (high emissions) by 2050. Note that this is the average MJT; year-to-year natural variability is greater than these ranges. Incorporating year-to-year variability, the upper end of the model range (90th percentile) under high emissions (RCP8.5) by 2050 indicates an MJT of 28.7°C (Figure 3, bottom left). The information tiles (Figure 3, right) summarise the information in the plots.

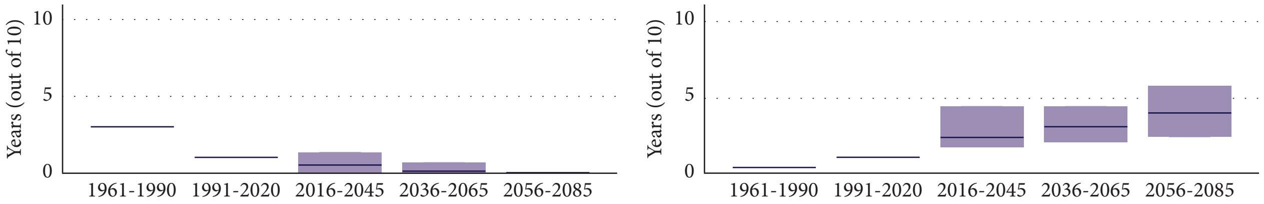
We can further consider changes in extreme years using the platform. Figure 4 indicates how the frequency of this "extreme year" may change in the future. For example, by 2056–2085, under RCP4.5, the chance of experiencing an MJT of below 21.8°C (the lower threshold experienced in the 1991–2020 period) is likely to be close to zero (Figure 4, left), yet for this same timeframe an MJT of 26.5°C, the upper threshold from the 1991–2020 period, may be exceeded around 3.9 (2.3–5.7) years out of 10 (Figure 4, right). This type of information may inform management decisions around variety selection for a particular region (refer to the discussion part).

Seasonal rainfall outlooks provide insights into decisions made in the current season. For the wine industry, seasonal rainfall outlooks are useful to inform planning, in particular irrigation scheduling and disease management. The outlooks are probabilistic, providing the chance of receiving a certain amount of rainfall for the next month or season (Figure 5).

An indication of the past accuracy of the outlooks is also provided. Past accuracy is a measure of how well the model has performed for the same selected time of year in the past. Accuracy is often tied to the evolution of large climate scale drivers such as the El Niño Southern Oscillation and Indian Ocean Dipole. These drivers have a strong impact on seasonal to annual Australian rainfall and temperature (e.g., [49]. In autumn, these drivers are still evolving and are often in their "neutral" phase and so there tends to be lower skill in predicting autumn climate. By winter and spring these drivers have matured and are more predictable, so accuracy of winter and spring outlooks tends to be higher especially over eastern parts of the country.

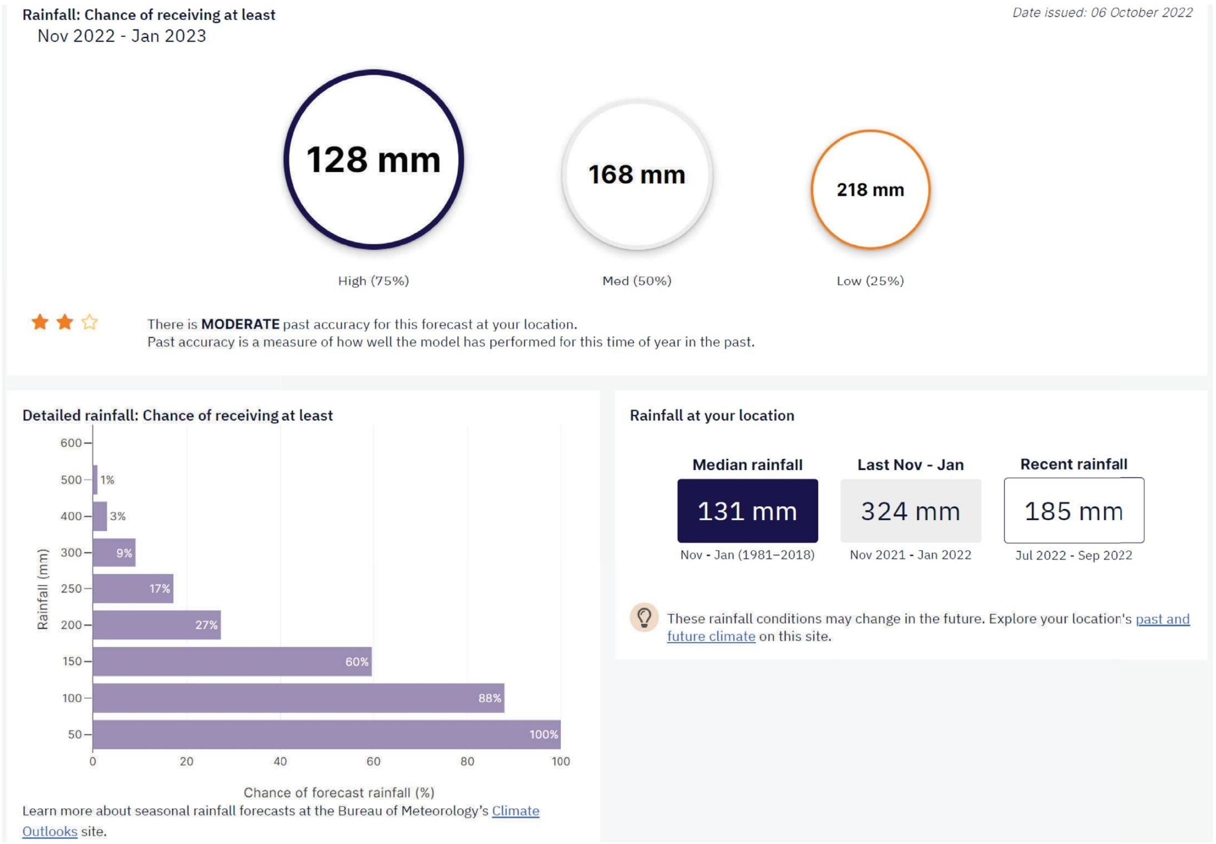
3.1. *End-User and Stakeholder Engagement in Action.* "Likely incidence in ten years" tool

As described above, the CSA platform has been developed using a user-centred design approach. Here, we present an example of how this approach has been implemented.



(a) (b)

Figure 4: Number of years (out of 10) with mean January temperature (MJT) (°C) below 21.8°C (a) and above 26.5°C (b) under RCP4.5. The range on the boxplots indicates future projections across different climate models. Data for past climate sourced from AGCD [41, 42] and future projections are from eight CMIP5 models.



Rainfall: Chance of receiving at least

Nov 2022 - Jan 2023

Date issued: 06 October 2022

There is **MODERATE** past accuracy for this forecast at your location.
Past accuracy is a measure of how well the model has performed for this time of year in the past.

Detailed rainfall: Chance of receiving at least

Learn more about seasonal rainfall forecasts at the Bureau of Meteorology's Climate Outlooks site.

Rainfall at your location

Median rainfall	Last Nov - Jan	Recent rainfall
131 mm	324 mm	185 mm
Nov - Jan (1981–2018)	Nov 2021 - Jan 2022	Jul 2022 - Sep 2022

These rainfall conditions may change in the future. Explore your location's past and future climate on this site.

Figure 5: Seasonal expected rainfall for the season ahead (next 3 months) with a certain (75%, 50%, or 25%) "Chance of receiving at least" a given rainfall total is indicated by each of three circles (top), or a given rainfall amount (for the coming season (bottom left), or different periods' rainfall totals (1981–2018 median), last year's seasonal rainfall, and this year's previous season.

User feedback was received, acknowledged, and used to drive the development of the new tool (Figure 6). This shows how users play a key role in building the CSA platform.

3.2. Map View Tool. Another example of how user engagement is driving the development of the CSA platform can be seen in the prototype "Map view tool." This tool was developed based on user desire to see information at a broader spatial scale, rather than for an individual location. A visual example of the tool is given in Figure 7. The tool, which is currently being tested with users, serves up the data in a map view and gives users the ability to select among the different commodities, related indices, and for current and future periods (under different scenarios). Single model or ensemble averages can also be selected (Figure 7). In this example, the ACCESS1.0 model forced under RCP4.5 is illustrated. The "pop-up" (Figure 8) appears when the user clicks on the "yellow pin" grid cell (refer to Figure 7), indicating the mean and 10th–90th percentiles of year-to-year variability in MJT (°C) across past periods and into the future, with results from all eight models included. The RCP scenarios can be toggled on/off, with RCP4.5 (Figure 8). This tool may be particularly relevant to users who desire to explore and compare climate changes across a broad region.

The new CSA prototype tool (released July 2022) includes a "Likely Incidence in Ten Years" tool. This customisable threshold tool was developed in response to user feedback asking for a more intuitive presentation of the climate data. The tool's development was influenced by users asking questions around other CSA features such as *"How often would we be on that average line?"* as well as comments being made about *"good-, bad-, very wet-, or very dry-years"* users had experienced. Different ways of presenting these data were explored, with the table display (below) being well received, with articulation of likelihood and frequency of events, relating to hottest-, driest-, or the coldest- and wettest conditions. The example below shows the average frequency of exceeding MJT thresholds (years out of 10) for Rutherglen across past and future periods (the full range of these results is presented more clearly on the platform).

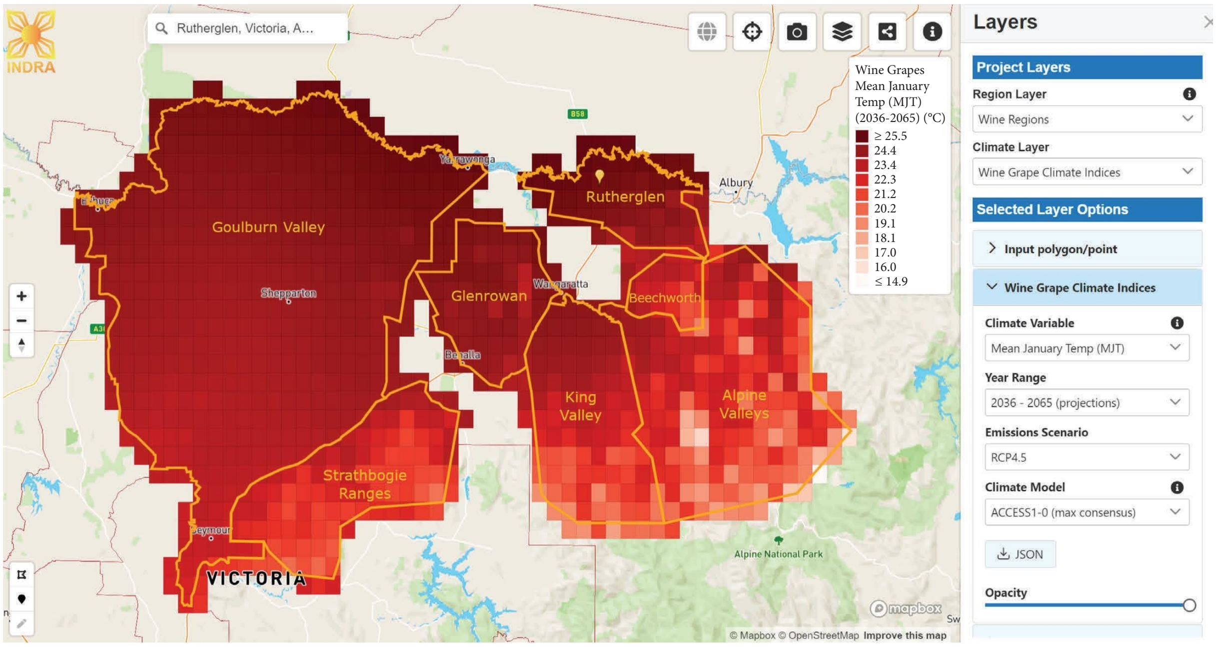
Year Range	Number of years with mean January temperature (MJT) below 21.8 (°C)	Number of years with mean January temperature (MJT) above 26.5 (°C)
1961-1990	3 in 10 years	0.3 in 10 years
1991-2020	1 in 10 years	1 in 10 years
2016-2045	0.5 in 10 years	2.3 in 10 years
2036-2065	0.1 in 10 years	3 in 10 years
2056-2085	0 in 10 years	3.9 in 10 years

The preferred definition of 'thresholds' varied amongst end-users, with some preferring to see changes in frequency of recorded historical extremes, while others wanted to use their own 'good' and 'bad' years' experience. Both options have been made available on the platform.

As a result of the new "Likely Incidence" tool, discussions between users and the CSA team now focus on what the information means. For example: *'What will farming be like in this type of environment?'*, rather than about how to read and interpret the data.

Using this information about projected changes to the frequency of climate events enables farmers to better visualise farm management going forward. In discussions, they now consider actions that could alleviate some of the anticipated challenges, without needing to discuss the science of climate change. Through exploring the platform and related discussions, CSA therefore assists in increasing farmer understanding of their individual future climate challenges and the types of decisions they may need to make to adapt to future farming scenarios. The engagement component of the CSA Program remains ongoing, with user feedback continuing to be incorporated into the platform.

FIGURE 6: Linking stakeholder feedback to platform outcomes "likely incidence in ten years" or number of years (out of 10) tool (see Figure 4).



Rutherglen, Victoria, A...

Layers

Project Layers

Region Layer: Wine Regions

Climate Layer: Wine Grape Climate Indices

Selected Layer Options

Input polygon/point

Wine Grape Climate Indices

Climate Variable: Mean January Temp (MJT)

Year Range: 2036 - 2065 (projections)

Emissions Scenario: RCP4.5

Climate Model: ACCESS1-0 (max consensus)

FIGURE 7: Mean January temperature (MJT) (°C) for northern Victorian wine regions (yellow boundaries) for 2050 (2036–2065) under RCP4.5 for the ACCESS1.0 GCM (global climate model).

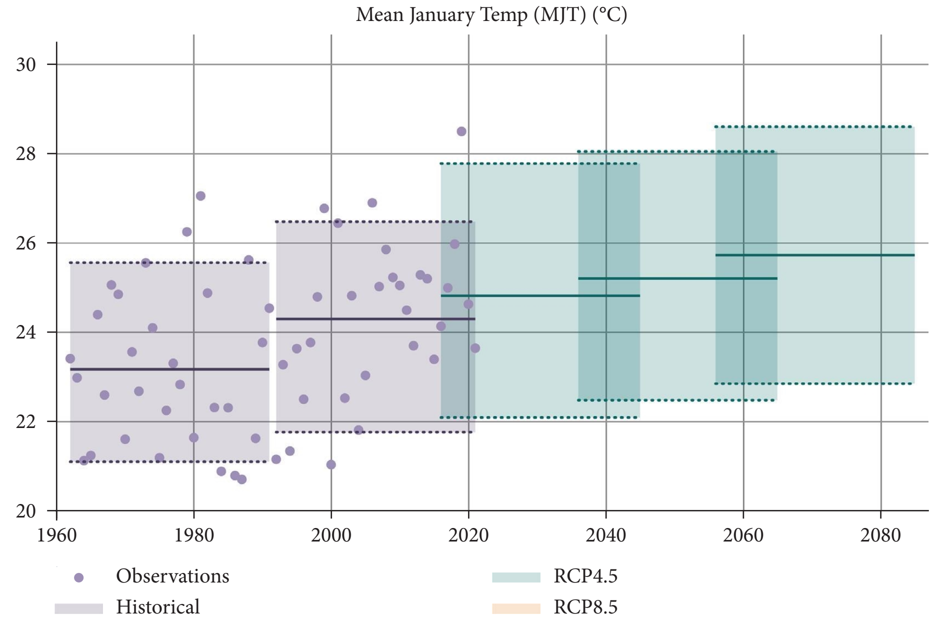


Figure 8: Range of MJT (°C) for past periods (1961–1990; 1991–2020) (purple with individual years indicated with dots) and projected 2030 (2016–2045), 2050 (2036–2065), and 2070 (2056–2085) average and range (10th to 90th percentile) of MJT (°C) (medium emissions, RCP4.5; green), an example Rutherglen grid cell pop-up window showing MJT observations and projections.

Further user testing will determine whether this tool is presented on the public facing CSA platform or whether further development is required to ensure its utility. This again highlights how users can have a direct influence on the development of a tool being presented on the CSA platform.

4. Discussion

The CSA platform provides wine-grape relevant climate indices that can be used for planning at a range of decision time scales (e.g., selecting wine-grape varieties that match the future climate of a region).

As described for Rutherglen, depending on the emission scenario, by 2050, MJT might increase from around 24°C currently, to 25.2°C (low emissions) or 25.8°C (high emissions) by 2050 (Figure 2), remembering also this is the average MJT and year-to-year natural variability is greater than these ranges. Noting these shifts, planting suitable varieties will help grapes ripen at a time when they have the best chance of retaining desired quality attributes. A compelling aspect of the CSA platform is that for any location, it is easy see if there have been any notable changes through the past climate, and better understand what may evolve in future. Over the longer term, therefore, growers can change varieties to better fit with the warmer projected climate. While the CSA platform does not attempt make varietal recommendations, much literature matching varieties to climatic characteristics of regions is available for Australia (e.g., [27]), and through using a global analogue approach [50].

The CSA platform presents different measures of growing season temperature: GDD (Oct to Apr) (°C); MJT (°C); average growing season temperature (Oct to April) (°C), as these relate to the variety suitability. Some indices were not selected for the following reasons. For example, Hall and Jones [20] evaluated both GST and BEDD for Australia's wine-grape growing regions under future climate change. They note that BEDD is less useful for considering suitability for hotter regions as it includes an upper threshold of 19°C [27]. Jarvis et al. [8] evaluated several indices for Australia wine-grape growing areas to consider maturity timing. The Huglin heat sum index, similar to the BEDD though not capped and slightly modified according to latitude, was assessed. They found the HI was problematic for application in Australia due to the latitude adjustment feature being less appropriate in Australia than in the northern hemisphere. The versatility of the platform enables a range of different metrics to be re-assessed and or introduced later if deemed helpful by users. Capability is also being built so that users of the CSA platform can customize commodity indices based on their lived experience.

Users of the climate data should acknowledge the uncertainties and limitations associated with the information presented on the CSA platform and consider how these might affect their conclusions and the confidence that they express in them. For example, the detailed application-ready projection data are a useful guide to plausible future climate conditions. However, the full uncertainty in future climate conditions is not reflected as there may be local effects on climate changes that are not represented by global climate models. This is most likely to be the case in mountainous or coastal areas. The CSA platform is evolving, which also means that data sources may change (or new data added), in response to user requirements. This may include the addition of new climate projection sources.

Confidence in a climate projection is a measure of how plausible the projected range of change is for a given emission scenario. Confidence ratings are assigned to projections based on multiple lines of evidence including how well our GCMs simulate key features of the climate system (e.g., do they simulate El Niño events well?), and how well we understand the drivers of change and how coherent the projections are with past observed climate trends. Across Australia there is high to very high confidence in temperature projections, including minimum and maximum temperature extremes such as heatwaves and frosts. The confidence in rainfall projections across Australia and for specific seasons is more variable. For example, in southwest Western Australia, there is high confidence that there will be a continuation of the trend of decreasing winter rainfall but on the eastern seaboard, decreases in winter rainfall are projected with medium confidence. Regional climate change information, including associated confidence levels are reported for Australia (see [19]).

Regarding the historical climate data, the Bureau of Meteorology has a large network of manually read and automated rain gauges across Australia, but it is not possible to place this equipment every few kilometres. While these stations provide rainfall data at point locations when available, gridded analysis utilises computer modelling to provide rainfall information in much wider areas. This is important as it means an estimate of rainfall conditions can be provided in data-sparse areas and provides a consistent coverage across Australia and over time. However, this means that the closest grid point to a particular location will represent both temperature and rainfall from several nearby stations. For this reason, the rainfall, and related frost risk, at any particular grid point might not be the same as the rainfall at any single gauge. Good understanding of a property's mesoclimate as it relates to the surrounding area is especially important in this regard.

The CSA platform is not designed to replace other forms of climate information used in specific industries. We encourage users to complement their exploration of the CSA platform with other relevant information which may influence production including soil type, landscape aspect, access to water, or logistical constraints. This assessment further does not account for a number of other factors that will influence the outcome from shifts in climate:

(i) Other weather variables (e.g., wind (important in the calculation of evapotranspiration), cloud)

(ii) Different adaptation practices which can be implemented. For example, the use of reflective sprays or trellis type, application of winter irrigation, or pruning strategies.

(iii) Influence of stored soil moisture on plant water balance, being affected by soil type

(iv) Timing and intensity of rainfall, which can influence yield and quality

(v) Access to water from dams or irrigation schemes

(vi) Varietal differences in the time of the growing season or potential phenological shifts to the growing season resulting from climate change

(vii) All climate-related decisions are only part of the many other factors influencing on-farm operations

A case in point is that a minimum temperature threshold does not necessarily represent a frost event with other conditions also contributing (wind, soil moisture, proximity to water body, land cover, and vineyard orientation). Further, occurrence of frost is not the same as damage from frost noting frost mitigation strategies can modulate potential risk (e.g. [35]). Thus, this minimum temperature threshold approach represents risk potential, not a frost or frost damage prediction.

We note the extreme heat metric is useful for considering historical and future trends in the potential for damage however, the scaling method used to create the projections, delta scaling [19], does not account for any changes in the sequencing, duration and/or frequency of weather events (e.g., increased duration and/or frequency of hot days).

The CSA platform is receiving positive feedback from the agricultural community. With the introduction of the "Likely Incidence in Ten Years" feature, conversations with end-users are now not only about how to navigate the platform and understanding the data, but about how management practices may need to change in a future climate. This transition is key to successful industry (and more broadly, national) preparedness for climate change. These conversations are being further developed by the CSA team, ensuring this beneficial interaction continues.

Feedback from the wine industry already enacted:

> "Would love to have the grapevine commodity on the platform as soon as possible, happy to advise on the indices."

While some are yet to be incorporated:

> "I'd would like to see data that shows bushfire projections for the future 2040-2050 climate for our regions."

Regarding climate change adaptation methods, we were told:

> "We can change the trimming of the vines, to protect from sun in years with very high heatwaves, canopy cooling with frost sprinklers pulsing at night. Under-vine sprinklers are also cooling techniques. Mulching, composting to conserve water and the keep the humidity lower in the vine canopy."

5. Conclusions

The CSA platform is a timely addition to the farmer and advisor information-toolbox to assist with planning in a changing climate. The information is targeted to agricultural production at a commodity level across Australia, with a spatial scale that aims to deliver nuanced climate-related information. This ground-breaking initiative provides national access to past and future climate information on one platform and is targeted to different agricultural commodities including wine-grapes with users and experts responding very positively regarding its utility. Assistance with planning decisions and discussions around climate variability and climate change is available for many Australian farming districts and is a key focus for continued research in all agricultural industries. Further development of the platform, driven by user needs, endeavours to increasingly improve its' functionality. [51].

Data Availability

The platform utilises the following data for delivery at national scale: (i) Historical temperature and rainfall data from the Bureau of Meteorology. (ii) Rainfall and temperature projections for 2030, 2050, and 2070 from CSIRO and the Bureau of Meteorology (https://www.climatechangeinaustralia.gov.au) for medium (RCP 4.5) and high (RCP 8.5) scenarios. (iii) Historical and projected surface water data from the Bureau of Meteorology. (iv) Seasonal Forecast data from the Bureau of Meteorology.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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