Report for the Deep South National Science Challenge (DSC) project ‘Climate, water and wine’

A systematic review of climate indices used to evaluate precipitation and rainfall changes and their effects on grape production

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AP reviewed was involved in all stages of the report and wrote the report, NK led the systematic review search and developed its methodology, JF contributed to reviewing articles and providing summaries, and editing the report.

Executive summary

Climate indices are defined as a calculation (may be as simple as number of days, or summation of precipitation for example) over a period of time that can be used to describe the state and changes in a variable (in this case precipitation) under investigation. Indices are particularly relevant for characterizing the potential effects of climate change on agricultural and horticultural production as they are used to describe climate trends over time, and for future climate change simulations to understand potential impacts. Here, we used systematic literature review methods to answer the following question: "Are there examples of bioclimatic or ecoclimatic indices used to evaluate precipitation and rainfall changes, or the effects of these annually on grape production?" The aim was to review and assess different climate indices that include the meteorological component of water availability, precipitation. The context in which each index was applied was evaluated for the index's usefulness to summarize precipitation based trends, and to inform modelling of precipitation changes under different scenarios of future climate change.

Specific inclusion and exclusion criteria for the systematic review were set which resulted in a search chain of 410 references for the period 2005 to 2022. After an initial title scan, this was narrowed to 80 references, and following an abstract scan and reading of the selected articles, 44 articles were reviewed.

The resulting indices have been organized into the following three categories: A) those based on rainfall only; B) those that empirically combined temperature and precipitation and C) those that took account soil water status and evapotranspiration. A total of 25 subgroups or individual indices were identified.

Group A) indices - based on rainfall only - were often the simplest to calculate, as they were a direct reflection of this meteorological variable. However, given that grapevine water needs are dependent on the influence of temperature, Groups B) and C) are more relevant in this context. Group B) had limitations in that there was little processed-based justification of how temperature and precipitation were integrated in the indices, and didn't account for soil based phenomena that critically change plant water needs. In group C), there were generally clear biophysical reasons for the indices parameters. However, there were many similar indices in Group C), approximating relationships between precipitation and evapotranspiration.

Key situational contexts for application were identified across all reviewed literature: historic and future climate change; site choice; terroir zoning/downscaling climate; general seasonal and site characterization/inter-annual variability; irrigation decisions; yield-quality relationships. Although many indices did not cover all categories, it is possible in future work for them to be applied to other categories.

Finally, to determine the utility of indices for understanding future conditions, initial application of each indices is one approach. Alternatively other options such as integrated or composite indices, or a hierarchy of these reported indices may be developed to aid decision making and practical application. This will require testing these against known datasets.

Introduction

Water management for crop production is a key concern in the context of climate change (IPPC, 2022). Changes in mean climatic conditions, coupled with increased climate variability means that there is growing risk of more frequent and severe floods and drought by the end of the 21st century (IPPC, 2022). At the same time, it is anticipated that a warming climate will result in an increase in crop water consumption of up to 50% compared with early 21st century (de Fraiture and Wichelns, 2010). When considering drought, where water demand exceeds water supply, its impacts are derived from the effects of precipitation and temperature changes influencing one of five usable supplies: soil moisture, ground water, snowpack, streamflow and reservoir storage (McKee et al., 1993). Climate change will influence all these supply sources. In order to ensure effective planning and decision making, robust monitoring of water availability and demand will be critical.

Grapevines are considered low water-need crops, with examples throughout the world of dry farming. However, water excess and water stress each can have consequences for grapevine growth and development (Table 1). Seasonal changes in vineyard water availability depends on meteorological conditions of precipitation and temperature, management interventions like irrigation which all impact water availability and soil type, moisture and conditions, all of which have consequences for grapevine growth and wine quality (Moral et al., 2016). With crop water consumption being a key concern for the future, it is possible that drought effects may lead currently dry farmed wine regions to consider irrigation to maintain productivity. Other regions already dependent on irrigation may require greater water quantity, and these demands, alongside competing needs by other crops or industries, may put the viability of grape production at risk. The availability of water in this context to supply new or additional irrigation also comes with its own uncertainty and planning.

Table 1. General impacts of water stress or water excess at key phenological stages.

Phenological phase	Impact of water stress of growth and development at this stage	Impact of water excess (logging) at this stage
Harvest- budburst	Irregular budburst	Root asphyxiation, root rot
Flowering (period including approx. 2 weeks before, 2 weeks after	Flower abortion Poor inflorescence primordia formation for the next season PBN?	Poor capfall (caps stick) leading to poor fruitset
Bunch closure to veraison	Delayed ripening Smaller berries Severe = fruit abortion	Disease pressure
Veraison to harvest	Mild = smaller berries, higher skin-to-pulp ratio Medium = shrivel Severe= structural damage to xylem, fruit abortion	Disease pressure

One way to ensure more effective crop management is through the use of ecoclimatic or climate indices. Ecoclimatic indicators or climate indices are defined as a calculation (may be as simple as number of days, or summation of precipitation for example) over a period of time that can be used to describe the state and changes in a selected variable. Often these indices relate to set calendar times in the year, approximations of growing seasons, or in the case of ecoclimatic indicators, they are calculated over phenological periods (Caubel *et al.*, 2015), directly relating the change in water availability to key times of water needs for the grapevine.2018; Zito et al., 2023, plus those in the review below). A range of ecoclimatic indicators have been applied at different scales (local, regional, national and internationally) and different crops (Caubel *et al.*, 2015, 2018; Marjou and Garcia de Cortazar-Atauri, 2019; Morales-Castilla *et al.*, 2020) in recent years. However, there is little consensus in the literature, and only limited information available to help guide selection regarding which index to use and why.

The majority of previous studies worldwide on grapevine that have used climatic indices, have focused on the effects of temperature increases on grapevines as the result of climate change, investigating changes in historical harvest dates or earlier phenology, or applying indices in projected changes in climate change scenarios (for example Ausseil et al., 2020; Chuine et al., 2004; Duchene and Schneider, 2005; Jones et al., 2005; Petrie and Sadras, 2008; Morales et al., 2020; Webb et al., 2012). Due to this focus, most index development to date has been based on elements of temperature (Moral et al., 2016). For wine and grape production, however, water availability is the key climatic variable: ensuring adequate supply at the right time, now and into the future.

There is an urgent need therefore to better understand and assess the availability and suitability of climate indices for water availability. The interaction between grape phenology and water availability in a changing climate will be contingent upon complex interactions, dependencies, and feedbacks, and therefore any indicator must be capable of capturing these interrelationships. The use of indices or ecoclimatic indicators is one method to assess the climate change impact on water availability.

In developing or applying existing indices for water availability, the first step is to understand if and how the meteorological variable of rainfall, impacting water availability in vineyard, may change under future climate scenarios. The second step involves linking changing water availability specifically to the development of the vine (phenology), where the impacts may cause positive or deleterious effects on yield, quality and vine health.

These meteorological factors do not operate in isolation however; it also is necessary to understand the combined effect of warming and water availability in the context of climate change; as temperature increases there is a potentially negative effect on the availability of surface water resources and increased water demand predominantly as a result of evapotranspiration (Vicente-Serrano et al., 2010). This is particularly important in the context of dry farming, which relies on rainfall as the main water source (Ramos et al., 2012). Therefore, understanding the balance between rainfall and evapotranspiration can result in a deeper understanding of water availability and water needs for grapevine growth in the future.

The aim of this review is to systematically identify and assess, for the first time, the key indices that have been developed to evaluate water availability for grapevines in the context of climate change projections. Using systematic literature review methods, we identify 25 subgroups or different indices, drawn from 44 papers. Indices are reviewed, assessed and categorised into three groups, based on their potential application for understanding changes in rainfall and precipitation. The potential application of all indices for climate change was considered. By evaluating these different indices, new insight can be developed with respect to their utility. Based on these findings, selected indices will then be applied to the Marlborough region, to help characterise future water availability and demand, and its implications for the wine industry.

With the focus of the current DSC project on changes in water availability, this systematic review has concentrated on water coming into the system as ‘rainfall’ or ‘precipitation’, therefore all articles reviewed had a focus on the meteorological water component of rainfall, but many articles incorporated other indices, primarily temperature based. The identification of key indices through this review will serve as a basis for the models that will be tested under future climate change scenarios to help address the question: “What are the likely impacts of climate change and its interaction with the availability and demand for freshwater resources in Marlborough?”

Methods

Systematic literature reviews (SLRs) use repeated analytical methods to collect and analyse primary research studies. SLRs are the syntheses of primary research studies that use reproducible methods to identify and synthesise all relevant material on a specific topic. SLRs differ from conventional literature reviews by defining a review strategy, making explicit inclusion and exclusion criteria, and by being peer reviewed and pre-published for transparency (Berger-Tal et al., 2019; Bilotta et al., 2014).

Originally used primarily in health research (Liberati et al., 2009), they have more recently been adopted and applied to a range of topics and issues in environmental and conservation research and in climate change adaptation (Carr et al., 2022; Cradock-Henry et al., 2023; Owen, 2020; Taylor et al., 2023; Wiréhn, 2018). There are only a few examples of SLRs for the grape and wine industries (Abad et al., 2021; Previtali et al., 2022; Weaver et al., 2021). This is the first SLR of climatic indices for grape and wine production, specifically those involving precipitation. This SLR followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to undertake an SLR of bioclimatic and ecoclimatic indices in viticulture. Following PRISMA, we first defined the parameters of our search. In setting the parameters of our search, we created exclusion and inclusion criteria (see Table 2), as well as a template to collect metadata (see Table 4).

The first step was to confirm our research question for the SLR:

Are there examples of bioclimatic or ecoclimatic indices used to evaluate precipitation and rainfall changes or the effects of these on grape production?

The second step was to devise article screening criteria and to begin devising the SLR codebook. The exclusion and inclusion criteria used are listed in Table 1 below:

Table 2: Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Written in English	Not written in English
Published between 1st of January 2005 and the 1st of December 2022	Published either before the 1st of January 2005 or after the 1st of December 2022.
Indexed on Web of Science	Not indexed on Web of Science
Paper contains description of bioclimatic or ecoclimatic indices in use in grape production.	Contains indices in use in other crops or species
Peer-reviewed paper published in a journal.	Non peer-reviewed paper, conference proceeding, report, or other research output.

The third step was to develop and deploy search chains. Several preliminary searches of the Web of Science database were conducted using different search chains developed by the researchers. The final search chains used are summarized in Table 3 below.

Table 3: Search Chains deployed in Web of Science

Search Chain 1	ind* AND “water” AND rain* AND wine*	133 results
Search Chain 2	ind* AND “water” AND rain* AND grape*	224 results
Search Chain 3	ind* AND “water” AND rain* AND viticultur*	52 results
Search Chain 4	ind* AND “water” AND rain* AND vine*	291 results

Search Chain 5	ind* AND “water” AND precipitation AND wine*	93 results
Search Chain 6	ind* AND “water” AND precipitation AND grape*	123 results
Search Chain 7	ind* AND “water” AND precipitation AND viticultur*	39 results
Search Chain 8	ind* AND “water” AND precipitation AND vine*	204 results

Total References	768
Total after duplicate deletion	428
Total after deletion of conference proceedings	410

A title scan was completed on the 410 references and only relevant ones were retained, resulting in a selection of 80 references. An abstract scan of the 80 references was carried out, and those that did not provide evidence of relevant indices were excluded. Subsequently, further articles were eliminated if the article did not address indices, the body of the article was not available in English or was a conference proceeding. In the case of one abstract no full text of the article was available. This resulted in the final selection of 44 articles for review. The information was summarized to characterize the indices, the situational context in which they had been applied, and to evaluate their potential application for understanding changes in rainfall and precipitation. The indices were evaluated for their application in the reviewed articles, as well as the usefulness and limits of each index were summarised.

Articles that measured plant-based methods to evaluate water status were not reviewed as they are not climate indices (these methods are reviewed in Rienth and Scholasch, 2021), although there are now some relationships established between plant-based methods such as stem water potential or stomatal conductance and water-based indices (Bois et al., 2020;Lebon et al., 2003). While many studies included annual or growing season rainfall or monthly rainfall as part of descriptive characterisation or site, or embedded within indices calculations, only those that used it as an index are reported here. As the majority or articles reviewed originated from the Northern Hemisphere, dates reported align to the growing season there, unless otherwise specified. If systematic review references were not where the index was developed, and the original reference was provided, this is listed here and in the reference list although the article was not directly reviewed.

Results and discussion

Following review, indices were categorised according to one of three main types: A) those based on rainfall only and B) those that had a measure of precipitation adjusted by a temperature function (empirical precipitation-temperature relationship in the indices), and C) those that considered soil water status and evapotranspiration. Each study and the indices it utilised was also coded for key characteristics related to application context, including historic and futureclimate change; site choice; terroir zoning/downscaling climate; general seasonal and site characterization/interannual variability; irrigation decisions; yield-quality relationships (Table 4).

A) Precipitation or rainfall

1. Number of rain days (including indices of maximum number of consecutive wet or dry days)

The frequency of rain events in terms of the number of rain days has been used for delineating viticulture zone differences (Cancela et al., 2016) and applied in studying longer term trends in Ramos et al. (2012) (although no trends were found). This has been adapted somewhat further to assess the maximum number of consecutive wet or dry days annually (Ramos et al., 2012; Yang et al., 2022a), which is more specific to understanding the duration of wet or dry periods. The usefulness of rain day indices are in determining times of the year when rain is more or less frequent, and the cumulative indices indicate the duration of the rain period. However, this approach is limited in that it does not address quantity of rainfall, critical in determining water availability. If used in combination with indices or part of indices that sum quantity or evaluate the quantity in terms of water use/availability, this would overcome this limitation.

2. Annual rainfall

Rainfall for the whole year (in mm) is an index to calculate amount of rainfall experienced in grape growing regions. It is the simplest index to use that has been reported in these articles. Annual rainfall was used in many of the studies from the systematic review (see Table 4), often applied when investigating trends in climate change (past, present and projected) (Cardell et al., 2019; Iliescu et al., 2019), and studies relating to quality (Martinez de Toda and Ramos, 2019). Annual rainfall has also been used to characterise terroir zones, with variable results (Cancela et al., 2016; Bramley et al., 2020). As Cancela et al. (2016) identified in the context of their study sites, two sites or regions may have the same number of rain days and similar temporal patterns of change in rainfall but the magnitude may differ, which would be more clearly reflected in an annual summation. Bramley et al. (2020) found that for one site annual rainfall was a good indicator of terroir zones, but less so for another site due to high rainfall variability. Ramos et al. (2012) assessed a wide range of precipitation indices (see sections below) and found that within season variability often masked any longer-term trends in annual rainfall for their sites. Therefore a key limitation of this index is that it does not give any specificity of the impact of the timing of rainfall relative to the growing season, on grapevine growth, development and/or disease status.

3. Growing Season Precipitation

A common indices used in the reviewed articles was the cumulative rainfall during the grapevine growing season from a start date until harvest, or over a set number of months corresponding to a growing season (Table 2). The period for the growing season rainfall months differed across studies with the period from April to September commonly used (as for example in Fraga et al., 2018), however, the period from 1 January to 31 August, corresponding to the period of heat accumulation pre-budburst through to just before harvest or at harvest depending on the region, was also chosen (Fraga et al., 2017). Growing Season Precipitation indices were used most often to characterise directional changes in growing season precipitation (increases/decreases compared with other seasons) (Cardell et al., 2019; Laget et al., 2008), and was often related to quality and yield (Camps and Ramos, 2012; Ohana-Levi et al, 2022; Ramos et al, 2012). Some studies extended the general site and seasonal characterisation to more specific goals of characterising terroir zones, but with variable results for the index (Bramley et al., 2020; Cancela et al., 2016).

This approach is more closely related to the plant growth period than using annual rainfall. However, like annual rainfall, it does not consider the more detailed timing or intensity of rain.

4. Monthly, 'seasonal' or phenophase rainfall

These three indices are grouped together on the basis that their goals are similar: to characterise rainfall at set times during the growing season for the grapevine. Characterizing rainfall by months of the year provides more seasonally specific detail on when rain falls (intensity and seasonality) than growing season rainfall. No studies reviewed here reported monthly rainfall in an index form. Monthly values can be grouped to approximate the rainfall during seasons (three-month groupings) or key phenophases (budburst to flowering, flowering to veraison, veraison to harvest, and the winter period of harvest to budburst). Ramos et al. (2012) looked at accumulated precipitation in spring, summer, autumn and winter, breaking the calendar down for each season. Different examples of phenophase rainfall accumulation were identified within the review: Camps and Ramos (2012) and Bois et al. (2020) characterising accumulated rainfall over the key phenophases; Campos et al. (2016) for one key period, from the fixed start date of May 1 until harvest, approximating the period of spring through summer growth; Moral et al. (2016) considered precipitation during flowering (PDF), precipitation before flowering (PBF), and summer precipitation (SP) as key indices, where PDF corresponded to the total rainfall in June at the time when flowering began for their study, PBF calculated as the cumulative rainfall between October and 31 May, and SP corresponding to the cumulative rainfall from 1 June to 31 August.

From a viticulture perspective, these approaches are more useful than yearly summations, in that they represent a more critical analysis of when the timing of rainfall occurs relative to plant development; too much rain or lack of rain at key times can have a critical impact on plant growth and quality (see Table 1). There are advantages of using the phenophase approach to better understand drivers, and the role that the length of the phenophase has itself on water availability outcomes for the vine. However it does require more specific record keeping; to be able to investigate phenophase rainfall under current conditions, records of phenology must be kept and to apply phenophase predictions in the future, phenology must be simulated first to define the windows of interest. It is worth noting that in another study using a different index (Crop Water stress index), Yang et al. (2022b) found that phenophase-dependent water deficits were affected by multiple and correlated factors, including the length of the phenophase itself.

5. The Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI), as reported in McKee et al. (1993), was developed in South Africa as a drought index, and can be used for different time scales and at different geographical scales, for example being used for 3-monthly summations corresponding to seasons, or approximations of phenophases, or for annual purposes. The assumption of the SPI is that rainfall is the most important climate factor influencing drought. This index compares a total precipitation at a location over a set time period (e.g., number of months) compared with the long-term rainfall distribution. Therefore the output is not a measured (mm) summation of rain, rather a relative difference to the long term rain. While this index is included here as it was mentioned in Araujo et al. (2016), it was not applied in any of the reviewed articles, with Araujo et al. (2016) preferring to use the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) which includes evapotranspiration as well (see below).

6. Precipitation Concentration Index (PCI) (Oliver 1980).

The Precipitation Concentration Index (PCI) was developed to characterise areas with pronounced wet/dry season and only has precipitation as an input variable. It involves analysing the average precipitation over that specified period, and working out how uniform precipitation is during that period. This index was used in only one study by Di Carlo et al. (2019), where it was found to not correlate with grape harvest dates in a warming climate. As this index focusses on assessing uniformity it is useful for describing spatial and temporal precipitation patterns.

7. Rainfall intensity indices

Rainfall intensity indices can be broadly grouped into three categories: i) those indices that capture maximum rainfall during a short defined time period. This would include 'Growing Season Precipitation' indices as part of this group, but could also scale to indices over shorter periods than seasons and months (e.g. 24 hour period); ii) precipitation over a set period divided by the number of days for the period and, iii) indices that look at accumulated precipitation over a period (in mm or number of days) and its deviation from average trends. Di Carlo et al. (2019) used the second approach with precipitation intensity being evaluated as the annual precipitation divided by the number of rain days, to assess how this influenced grape harvest dates in a warming climate. In the characterisation of climate trends for a 60-year period, Ramos et al. (2012) used approaches i) and iii) by testing the maximum annual precipitation recorded within an hour, the number of days with precipitation exceeding the 95% percentile, and the percentage of annual rainfall in events over 95% of the total for both annual and across all season periods. The strength of these indices is that they address extreme precipitation relative to averages, and extremes within a short period of time (even down to one hour if required) However, Di Carlos et al. (2019) found that precipitation intensity does not account for the effects of the total amount of precipitation in driving changes in grape harvest dates, which suggests this index should not be used in isolation.

Summary of rainfall-based indices

All rainfall-based indices are simple to use given the availability of data, and depending on the data source (from regional, local of vineyard level installed rain gauges/sensors), can be used at various geographical scales to understand changes in precipitation. Most indices do not transform the data, rather reported accumulated mm values of rain, so can reduced accumulations of errors, or limitations imposed by model assumptions when characterising trends. Their success in different applications varied among studies, and generally there was no consensus on which indices to use, although growing season precipitation and or seasonal/phenophase precipitation were applied most often. One challenge is that the period over which the index is determined can affect the interpretation of the significance of the results as well as the sensitivity to other the influence of other factors. For example, a short rainfall intensity index (24 hours) has little influence of other factors but the understanding it provides is limited to short time specific timeframe, and may be useful for the case of extreme weather events. Furthermore, in using just precipitation-based indices, particularly for drought, Vincente-Serrano et al. (2010) succinctly summarizes that two assumptions need to be met 1) the variability of precipitation is more than variable of other factors such as temperature or ET affecting water availability and that 2) other variables affecting water availability variability don't change with time (or seasons). In some application contexts – such as longitudinal studies or climate change projections – it is not possible to meet 1) above, due to the importance of temperature as a variable in its own right, as well as its integrated role in drought. Finally, a limitation of all these rainfall-based-only indices is the do not account for temperature, evapotranspiration or other soil properties that affect water availability to the plant.

B) Precipitation based indices that also incorporate temperature

This group of indices use some measure of precipitation plus a measure of temperature in the index calculation. These indices were less commonly applied in the papers reviewed. Only four articles used these indices.

Zaldea et al. (2021) tested a range of temperature indices that incorporated temperature and precipitation:

- the hydrothermal coefficient which weights growing season precipitation divided by a measure of Growing Degree Days base temperature 10 °C (GDD_{10} (Selyanianov, 1928)
- the de Martonne aridity index which is the annual precipitation divided by the average annual temperature base temperature 10 °C (De Martonne, 1926)
- the vine bioclimatic index which includes a GDD_{10}, and precipitation during the growing season and number of days above 10°C during the growing season (Constantinescu et al. , 1964) and
- the oeno-climate aptitude index with includes a GDD_{10} and an adjusted annual precipitation component (Teodorescu et al., 1987).

The authors determined different applications for these indices and also when they did not work so well to reflect and precipitation trends. For example, the hydrothermal coefficient indicated a decreasing trend due to decreased irrigation; the de Martonne aridity index was used to group seasons by aridity trends; the precipitation coefficient simply reflected dry years and rainy years; the vine bioclimatic index was highly variable, and the oeno-climate aptitude index was used to determine white versus red varietal suitability.

Heydari and Movaghari (2021) also used the de Martonne index and the hydrothermal coefficient to evaluate changes in indices over time, but found no significant changes over time for these indices. Iliescu et al. (2019) employed the hydrothermal coefficient to assess historic climate trends over time but it did not add much information in addition to annual rainfall, and Lorenzo et al (2016) also used the Hydrothermal Index to evaluate mildew risk for future climate conditions. The research by Lorenzo et al. (2016) also raised a concern with the index; on current data it performed more poorly than temperature-based indices due to the spatial variability of precipitation.

While these are examples of composite indices, and may be useful to integrate temperature and climate, they are limited insofar as the temperature components have assumptions about base temperatures for GDDs and weighting factors. Similarly, the precipitation is weighted in these indices. Furthermore, Heydari and Movaghari (2021) also discussed that in their study they tested both precipitation-based indices and temperature indices and found that there were no changes in the precipitation indices, despite major changes in temperature-based indices (such as the Huglin index). This may affect evaporation and irrigation, pointing to the need to go beyond precipitation driven indices, particularly in the context of climate change assessment.

C) Indices developed based on precipitation and evapotranspiration

Evapotranspiration

While this review focused on capturing literature that evaluates the change in natural water availability via rainfall. Evapotranspiration measures are known for their ability to reflect variability in crop water and therefore represent an integration not only of precipitation or rainfall, but other climate factors.
Potential evapotranspiration is a key measure for determining irrigation scheduling (e.g. Jagosz et al., 2022), and soil–water balance models (SWB) focus on the soil-plant atmosphere interface, which is also used for irrigation scheduling (Campos et al., 2016), understanding harvest and yield responses (Camps and Ramos, 2012) and investigating how climate has changed using historic data (Duchene and Schneider, 2005).

The Penman-Monteith equation (Penman, 1948) is commonly used to approximate net evaporation from meteorological data used in climatic water balance calculations and has been used to estimate evapotranspiration in grapevines and many other crops. This equation includes irradiance, ground heat flux, air temperature, wind speed, vapour pressure deficit, rate of change of saturation of specific humidity with air temperature and can be assessed on a daily time step, so the data can be readily used for understanding index based summations. This annual evapotranspiration assessment has been used as an index in its own right, although other indices have developed that integrate evapotranspiration with other measures (see sections below).

Potential evapotranspiration (PET) is a function of reference evapotranspiration multiplied by a crop coefficient. The reference evapotranspiration is a function of temperature, and the crop coefficient is the ratio of evapotranspiration measured in conditions of sufficient soil humidity to reference evapotranspiration. PET estimations require knowing the Total Available Water (TAW), or water reservoir, at the beginning of the growing season to establish soil water balance. Estimating this is not without its challenges, as soil water balance varies at different sites depending on soil types, rootstocks, abilities of roots to extract water at different soil depths as well as variability introduced by assessment methods (Campos et al. 2016). Research has looked at estimating ET via remote sensing energy balance models overcome these challenges (e.g. Campos et al., 2016).

Given this review is focused on the inclusion of rainfall and precipitation in indices, as these are the climate parameters that directly influence input water in the context of climate change, it is likely that articles that only used PET for assessing current or future water availability were excluded by the systematic search strategy of this review. However it did capture articles that applied climate-water balance indices that included precipitation and evapotranspiration, and these are described below. The key limitation of whether the indices in this group below can be applied is the availability of ET information.

1. Climate Water Balance Model/ P-ETc index/Climate water deficit (CWD) index

Thornthwaite (1948) proposed a simple climatic water balance index (also an index of potential water shortage) that can be calculated as the difference between precipitation and potential evapotranspiration (PET). This is often incorporated in indices (see below).

The difference between rainfall and evapotranspiration, also referred to as the P-ETc index or the Climate Water Deficit (CWD) index, was used in several studies reviewed for this report. Duchene and Schneider (2005) determined a relationship between this index and the advances in phenology observed in their study. Ramos and Martinez de Toda (2012) used the index to characterise the climate between key phenological stages and related this to quality parameters in berries, and later applied the index in the context of climate change projections (Ramos and Martinez de Toda, 2020). These researchers were also able to demonstrate a relationship between increases in P-ETc (less water stress) and a long budburst to flowering period due to delayed flowering (Ramos and Martinez de Toda, 2022). Other researchers have used the index to examine climate change projections of regional change (Kapur et al., 2010), and have applied it to a period of a hydrological year (1 November to 31 October) to characterise past and future climate change projections (Hofmann et al. (2022). These examples indicate the period over which this index is calculated can be tailored to the aim of its application.

2. The Dryness Index (Riou, 1994)

Originally proposed by Riou (1994), this index reflects the soil water status, taking into account initial soil moisture, the daily precipitation, the loss of water through transpiration (defined by PET and the plant radiation absorption coefficient) and the loss of water that evaporates from bare ground (number of days with effective soil evaporation). This index is specifically calculated for the period 1 April -30 September, and is often used in combination with two temperature indices (Heliothermal index - an annual summation of temperature, and the Night Cold index – related to the night temperature during the ripening period) to classify viticulture climates according to a multicriteria climatic classification (MCCC) system of grape growing regions or sub-regional areas, as developed by Tonietto and Carbonneau (2004). Using the Dryness index within the MCCC, it can primarily be used to assess environmental suitability for grape growing, with the MCCC proposing zones, or classes, of climate based on this system.

The dryness index is perhaps one of the most commonly applied indices in viticulture identified in the systematic review (Table 2). It has been used to characterise local appellation/regional differences (terroir areas) (Aparecido et al., 2018; Cancela et al., 2016; Fraga et al., 2014) and to identify historical (Teslić et al., 2017; Mandic et al., 2022) or potential (Trbic et al., 2021; Martins et al., 2021) climate change effects for a region or regions of interest. Interestingly, Fraga et al (2014) used the dryness index and the MCCCS (Tonietto & Carbonneau, 2004) for an integrated assessment of 'terroir' and demonstrated that for the region of Iberia, temperate dry climates with cool nights dominated the characterisation of the region, with dryness being a key factor driving vine performance. This example also demonstrated that while water-based indices are valuable to understand potential future challenges in the context of climate change, specific interactions with soil type and synergies with temperatures will create localised effects.

Martins et al. (2021) noted that bias correction is needed for local adaption, and where they tested nine temperature and precipitation-based indices, the Dryness index as the one had the highest sensitivity to the bias correction step. This may represent one of the limitations of application if this step is not considered.

3. Standardized Precipitation Evapotranspiration Index (SPEI or SPE, Vicente-Serrano et al., 2010)

The Standardized Precipitation Evapotranspiration Index (SPEI) was developed by Vicente-Serrano et al. (2010), who modified the Standardized Precipitation Index (SPI) (rainfall based only index) to take into account the effect of temperature variability by incorporating evapotranspiration. The SPEI calculates the difference between the monthly (or weekly) precipitation and potential evapotranspiration (PET), as per SPI but uses a probability measure to determine if this difference is outside a standardised range. Potop (2011) created a classification of SPEI values where the values categorised sites into classes of 'extremely wet', 'normal' or 'extreme drought'.

The SPEI has been used to look at drought at different geographical scales from districts to farm scale (Araujo et al., 2016) and to understand adaptation to extreme events, such as drought, on a global scale in the context of climate change (Santillán et al., 2019). Araujo et al. (2016) observed that when looking at the relationship between SPEI and vine productivity, such as yield, that this index correlated better than rainfall or temperature, however, this correlation was only evident at the farm scale, It was hypothesised that SPEI characterisation at a regional scale was less successful due to the confounding influence of different farm-level irrigation strategies, and could be more easily attributed/understood with farm scale data in relation to irrigation application (Araujo et al., 2016). In application for impacts and adaptation to climate change, SPEI proved useful to demonstrate potential increased water deficits globally and to draw relationships between temperature indices (Huglin used in this study) and water indices (SPEI) for different countries (Santillán et al., 2019).

Recent critical evaluation of this index has highlighted that it should not be used alone to assess drought severity due to the index not directly corresponding to actual water shortage (difference between potential evaporation and precipitation, Zang et al., 2019). The index is also calculated based on a standardized scale making it difficult to compare between different reference time periods.

4. Crop Water Stress Index (CWSI)

The Crop Water Stress Index (CSWI) (Idso et al., 1981) is calculated based on the ratio of daily actual water update and daily potential transpiration. This index has been used to characterise potential CWSI of different viticulture zones, at key development times, demonstrating clear differences from flowering to harvest with maximum values obtained during berry formation (Bonfante et al., 2015), or in Yang et al. (2022a), where they focussed on understanding differences in the CSWI period for flowering-veraison (the critical period during phenological development for drought sensitivity). In a number of wine production countries in Europe, the CSWSI was used to assess vine drought conditions and the relationship to yield loss rate. For example, Colak and Yazar (2017) used it to evaluate the effect of irrigation regimes on water stress demonstrating a clear relationship of increased water stress and decreased yield, whereas Yang et al. (2022b) used it to investigate vine water deficits for flowering-veraison for downscaled region projection of water stress in the context of climate change. The strength of this index is combining soil characteristics with crop stress, and combined with phenophases, can be powerful in assessing stress at set times in the plant's development. However, it does go beyond meteorological inputs for understanding water needs, and the need for soil information may be a limitation if the information is not available or at an adequate resolution and local and varietal calibration is required.

5. Precipitation Deficit Probability Index

This index employed in Jagosz et al. (2020) aims to evaluate the rainfall deficit, calculated as a probability of occurrence relative to normal, medium dry, and dry years. The index incorporates evapotranspiration and precipitation, using the long-term averages of each as the baseline against which deviations (medium dry, and dry years) can be assessed. The index has been used to characterise monthly trends, and water needs of different growing areas, as well as trends of increased water needs over time, with an evaluation of the relative contribution of evapotranspiration versus rainfall to these trends. A strength of this index is the relationship to the long-term average baseline values, but this is also a potential limitation for application if these values are not available. Another limit is the output is probability rather than a unit of measurement (e.g. mm deficit of water), which may limit interpretation.

6. Water Deficit Stress Index (WDSI, Bois et al., 2020)

Bois et al. (2020) developed the water deficit stress index to better understand the importance of local downscaled rainfall for grape and wine production. This index couples soil water balance measures of water availability relative to soil water holding capacity (Lebon et al., 2003), i.e., the fraction of transpirable soil water (FTSW). To do this, the water balance model incorporates reference evapotranspiration, rainfall, daily solar radiation and daily air temperatures. Relative grapevine stomatal conductance is then determined from the inverse exponential model between the daily FTSW and grapevine stomatal conductance, as developed by Pieri and Gaudillere (2005). The combination of the Lebon et al. (2003) water balance model and the Pieri and Gaudillere (2005) inverse exponential model forms the WDSI. The advantage of this index is that it combines soil water balance with a modelled physiological plant response of stomatal opening and closing. It has also been successfully used in the context of phenological development, averaging WDSI for key periods of phenology development: budburst- flowering, flowering to veraison, and veraison to harvest. The development and application of this index has demonstrated the importance of characterising grapevine water status at a local scale (study carried out on 46 sites within 28km^2) rather than relying on regional water balance inputs, and found that the physical environment driven by soil variability had a greater influence on grapevine water status than rainfall variability. The limitation of this index is it may not be applicable in all areas, due to the need to collect and process local rainfall data. Furthermore, the Lebon et al. (2003) soil water balance model was developed primarily for use in flat terrain, and whilst there are model developments for sloped environments (Hofmann et al., 2014), they have not been tested/integrated into the WDSI.

7. Water Stress Index (WSI, Gaudin et al., 2014)

A water stress index was developed in Gaudin et al. (2014) based on determining the fraction of transpirable soil water (FTSW) at four key developmental times throughout the growing season: two times between flowering and veraison and two between veraison and harvest. To determine ‘stress’ metrics, the average FTSW is calculated for an area, with the FTSW threshold based on expert knowledge of stem water potentials (and then using existing correlations of these with FTSW to generate FTSW equivalents).

One challenge in implementing this approach is that the expert knowledge is required to define the thresholds, and that assumptions around the soil reserve recharge need to be made to be able to calculate available soil water (which is needed for FTSW calculation). However, this also represents an opportunity to be better adapt to localised knowledge. Furthermore, the authors successfully demonstrated that this synthetic water deficit index could be correlated to yield, and some quality metrics such as berry weight, and sugar and acid content per berry.

The use of FTSW in both WDSI and WSI has the advantage in that its calculation is based on rainfall, evapotranspiration, transpiration, evapotranspiration and total transpirable soil water, taking into account the role of water beyond just simple rainfall metrics or evapotranspiration.

8. Palmer Drought Severity Index (PDSI) (Palmer, 1965)

Despite this being a well-known index for drought in general, it was only used in one study identified in the current review (Carlo et al., 019). The PDSI is a soil water balance index calculated based on precipitation, temperature and available soil water content (see section on other indices below for explanation of AWC), therefore requiring this information as input variables. Positive values correspond to wetness and negative values to dryness. It is often computed over monthly periods. The one study that applied this index) found low to no significant correlation to the grape harvest dates in a warming climate (Di Carlo et al., 2019.) Given it takes into account three key variables, it could be considered as effective as some of the other indices in this section developed on rainfall and evapotranspiration but it is currently used less in viticulture.

9. Drought Stress Days

Hofmann calculated the yearly sum of drought stress days (1 May 30 September), where a drought stress day was defined as a day when the soil water content was less than 15% available water capacity at 2m. This threshold was proposed based on assumption that AWC at this depth is equivalent to Total Transpirable Soil Water (TTSW), and that the threshold of 15% was equivalent to a severe stress predawn leaf water potential calculation of -0.6MPa as defined in Hofmann et al. (2014). This is a recent proposition and given how it can be related directly to a plant water status measurement of predawn leaf water potential, it could prove useful in future applications at the vineyard or localised scale.

D) Other indices

The following indices discovered through the SLR approach use precipitation but their output does not clearly reflect this input variable.

1. Rausch Model

One approach by Moral et al. (2016) looked at developing a viticulture specific integrated index to determine “climatic suitability potential for viticulture” by integrating 10 climate indices into one assessment through the Rausch model, which combined probabilistic model and geostatistical techniques. The indices that were integrated included: [heliothermal index (HI), cool night index (CI), dryness index (DI), growing season temperature (GST), the Winkler index (WI), September mean thermal amplitude (MTA), annual precipitation (AP), precipitation during flowering (PDF), precipitation before flowering (PBF), and summer precipitation (SP). The influence of each climate index on the climatic suitability potential for viticulture was assessed. This method determined PBF and AP were the most influential climatic indices on climatic suitability potential for viticulture in the region of Extremadura, Spain. The study indicated that the relative importance of the different indices may differ by region, but the method would be robust to apply elsewhere. The integrated model/index also suggests that there are ways by which a more composite measure of climate that includes key precipitation parameters could be developed (see perspectives for further discussion on this point).

2. Water productivity indices

Water productivity (WP) indices have been used to relate the water use to production measures. The original indices in Rodrigues and Pereira (2009) was a ratio between yields and total water use (TWU) or between the value of the product and total water use. This was applied in Cancelas et al. (2016) to characterise differences in regions, but these authors also developed two more water productivity indices: pruning weight/ TWU and yield +pruning weight/TWU. The interest in this metric is that TWU corresponds to rainfall plus irrigation, so it integrates both water inputs and relates water use to production. Interestingly, Cancelas et al. (2016) demonstrated that WP alone did not distinguish differences between two areas being compared, but WP based on pruning weights or pruning weights + yield did. However, as a result, these indices are not strictly water-only-based indices like the others as they include vine metrics as well. Cancelas et al (2016) also summarized a limitation of WP is that they may be less sensitive in humid conditions where high vegetative growth occurred even at later phenological stages and that including the pruning weight can help account for this, which they successfully demonstrated in characterising two areas for two different cultivars in Galicia, Spain.

3. Available Soil Water (ASW)

This index goes beyond precipitation and evapotranspiration considerations only, considering all water inputs (rainfall and irrigation) and crop evapotranspiration and drainage. It featured as part of The Vineyard-Soil Irrigation Model (VSIM – https://sites.google.com/a/csumb.edu/vsim) which was used to simulate soil water. Ramos et al. (2020) applied this index to investigate the relationship between grape composition-ASW-water stresses under different weather conditions. This index has a dependency on soil data, as well as meteorological inputs of rain and temperature, and therefore potential evapotranspiration as well. It is likely this index has been applied to viticulture research elsewhere, but the focus of this review on rainfall/precipitation may mean that other articles not specifying this component of the index in the abstract were excluded.

The utility of this index is that it extends the integration of 'water' in terms of plant needs in the context of specific soil conditions, however, its dependency on being able to estimate available water capacity and its dependent variables may limit its application in cases where this information is not easily derived. When applied successfully, as in Ramos et al. (2020), vine water stress was quantified as a fraction of ASW, and used to determine within season differences in water stress between plots for different phenophases. The authors indicated it could be useful in the context of climate change where temperature is predicted to increase and soil water availability decrease due to increased evaporative demands.

E. Application of indices in the context of climate change

A key outcome of this review was to collate indices that could be used in the context of climate change. The systematic review results in 22 out of the 44 articles reviewed had used indices to determine historical data trends or future climate change projections, and only seven out of the 25 indices described were not used in the context of climate change application.

In the context of climate change, it is important to recognise that relying solely on precipitation may not reflect the water availability for the grapevine, due to the combined effects of temperature and the effects on evapotranspiration. Therefore, while precipitation-only-based indices has a role in describe the impacts of changes in this meteorological variable, those that integrate an approach that reflects more the outcome for water availability for the plant may be more useful. One challenge identified though, is the ability to use these indices at a scale that is relevant to the producer (Bois et al., 2020).

The interaction of changes in rainfall patterns and temperature was a key feature of many indices, but this relationship is not linear. In the context of climate changes studies, and the interaction will be highly dependent on the timing of climate changes relative to the phenological stages of the vine.

With so many indices available for use, further investigation is required into how to evaluate the relevance of the different indices and when and why different indices may be more suitable for application in the present research context of climate change. Results show that in some studies, the choice of indices was clear, and had been adequately justified relative to the hypothesis/-es, but in many cases other indices could have just as easily been applied. Although many indices did not cover all categories defined in Table 4), it is possible in future work for them to be applied to other categories, and their relevance for each to be critiqued. All listed indices could be potentially tested in the context of climate change. Further analysis (e.g., using principal components or other statistical techniques) may help determine which to use and why, and when – and in such a way, enhance their relevance for particular applications and contexts. This is critical in the context of climate change.

F. Perspectives

The results of the systematic literature review has highlighted the wide range of precipitation-based indices for grape production that have been developed and applied across diverse contexts. While many of these indices have foundations in well-developed concepts - such as the balance between evapotranspiration and rainfall - there are many different variations in inputs, and therefore potential differences in outputs in terms of evaluating water availability.

The proposition of developing integrated indices built from several of the reviewed indices or finding a method to prioritise (hierarchically) which indices to apply or for which situation has not been addressed in detail for application in viticulture. However, one article (Kanthavel et al., 2022) created what they termed an "integrated drought index" (IDI); this was not included in the main part of the review as it was not applied in viticulture. However, the abstract scanned highlighted some interesting considerations for review. The research summarized a range of commonly used drought indices from those built on single hydrological parameters (e.g. precipitation for Standardized Precipitation Index (SPI) (McKee et al., 1993), through to composite indexes such as the Aggregate Drought Index (ADI) which takes into account precipitation, evapotranspiration, stream flow, reservoir storage, soil moisture and snow water content to explore meteorological, agricultural and hydrological drought simultaneously (Keyantash and Dracup, 2004). The review process highlighted that many of these indices have not been applied in the context of viticulture. The IDI incorporated existing drought indices that reflect different drought phenomena : meteorological drought reflected in the Standardized Precipitation Index (SPI) based on precipitation only and Reconnaissance Drought Index (RDI) (Tsakiris and Vangelis (2005) based on precipitation and evapotranspiration; agricultural drought reflected by Standardized Soil moisture Index (SSI) (Hao and AghaKouchak, 2013) and hydrological drought reflected in the Standardized stream flow Drought Index (SDI) (Nalbantis and Tsakiris, 2009), developing and applying this composite index for application for 1 or 4-month periods. This article came up the literature review due to the probability method used to integrate the indices into one index being called 'vine copula' but fortuitously has demonstrated a range or more general indices they be used and not specific to viticulture, likewise methodological approaches to combine indices for a more integrated evaluation of water availability. From the systematic literature review results, it was demonstrated that approaches in viticulture had not yet looked at doing this, and so this approach and the other composite indices and respective methods addressed in the article, may be worth further investigation for application in viticulture to understand drought conditions now and in the future.

Plant water status measurements were excluded in this review process. However these measurements are useful in understanding at an individual plant level the water availability for plant growth and development (Rienth and Scholasch, 2019). These measurements require detailed sampling within a vineyard or area to get representation of the status. Given the time investment needed to make such measurements, it is difficult to produce detailed regional outputs of this, for understanding the current effects of water availability on plant performance. It then becomes even more challenging to produce a model to predict a plant water status measure such as stem water potential in the context of climate change and further controlled growth room experimentation or substantial historical datasets would be required to create a suitable index for prediction. However, there are examples where plant based measurements have been used in indices (Bois et al., 2020; Hofmann et al., 2023; Lebon et al., 2003) indicating the potential to do this in the future.

This review also highlighted that while the focus was on precipitation and rainfall based indices, the use of the term 'drought' or extending the search parameters beyond viticulture articles might highlight other indices or approaches. Also within the review, there were other 'indices' detected through the systematic review process, that did not necessarily include rainfall but may be of interest for drought assessment. One example was the topographic wetness index used in Ohana-Levi et al. (2022) and Bahat et al. (2021) to understand site specific spatio-temporal differences within a vineyard as is defined as the a measure of static soil moisture conditions within a pixel of an area. Its function takes into account the upstream contribution area (m^2) and the local slope, thereby not taking into account rainfall measurements itself. It therefore could act as a multiplier on static soil moisture measurements, but was not tested in this way in Ohana-Levi et al. (2022), rather used in statistical analysis to see if it was associated with spatial or temporal patterns in rainfall. It was found that the highest rainfall years were most correlated with this index (and differences with within site 'spatio' patterns) of grapevine yield.

While all indices reviewed depend on precipitation and some on temperature and or ET, the soil available water holding capacity and the available soil water are important measures beyond the meteorological inputs. Furthermore, as the water balance of a grapevine also depend on vine spacing, training systems further determining canopy characteristics, and soil management practices which will reflect site mesoclimate conditions, it is important consider these factors in terms of water supply and available precipitation (Hoffman et al., 2022).

Finally, it could be useful to determine whether or not 'parent' origins of these indices could be determined, linking back the indices to more historical references outside the scope of the boundaries of the systematic review. For example, Riou (1994) which was not part of the review, but the original research into the Dryness Index that was then subsequently employed in many of the review papers, despite the review papers not referencing one another. This analysis, would help highlight the pivotal works that have led to developing a diverse range of indices, and potentially inform further development and refinement.

Conclusion

A vast array of indices exist that evaluate the role of precipitation in viticulture, with some simply using precipitation, and others including other factors such as temperature and evapotranspiration. The review has summarized the key indices used since 2015 in the literature to address water requirement dependent on the metrological variable of rainfall, and highlighted that over 25 subgroups or individual indices have been used. Some like the Growing Season Precipitation or the Dryness Index were used in many studies and for many purposes, but other equally interesting indices such as the Drought Stress Days have only been used in one study to date.

While this review have focussed solely on grapevine based literature and the meteorological input of rainfall, the review has demonstrated a wide range of indices in use, and a wealth of approaches that are employed just for the particular question "Are there examples of bioclimatic or ecoclimatic indices used to evaluate precipitation and rainfall changes or the effects of these on grape production? "The challenge in applying these is now choosing which ones to use and why, and future work should evaluate the relative importance of these indices or look at developing composite indices that integrate several of these indices.

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Table 4. Summary of indices, references and applications.

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
Precipitation data based only							
Number of wet days	Cancela et al. (2016)			X			
	Teslić et al. (2017)				X		
Maximum consecutive wet days	Ramos et al. (2012)	X					X
Maximum consecutive dry days	Martins et al. (2021)	X					
	Ramos et al. (2012)	X					X
	Yang et al. (2022a)				X		X
Annual Rainfall	Bramley et al. (2020)			X			
	Cancelas et al. (2016)			X	X		
	Cardell et al. (2019)	X		X			
	Di Carlos et al. (2019)	X					
	Duchene and Schneider (2005)	X					
	Iliescu, M., et al. (2019)	X					
	Martinez de Todas and Ramos (2019						X
	Ramos et al. (2012)	X					X
Growing season rainfall	Camps and Ramos (2012)	X			X		X

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
	Campos et al. (2016)					X	
	Cancelas et al. (2016)			X	X		
	Bramley et al., 2020			X			
	Fraga et al., 2017						
	Fraga et al., 2018	X					
	Laget et al. (2008)	X					
	Martins et al. (2021)	X					
	Ohana-Levi, N., et al. (2022)				X	X	X
	Ramos et al. (2012)				X		X
	Teslić et al. (2017)	X			X		
	Yang et al. (2022b)	X					
	Iliescu, M., et al. (2019).	X					
	Yang et al. (2022b)	X					
‘Seasonal’ or phenophase rainfall	Bois et al. (2020)			X			
	Camps and Ramos (2012)				X		X
	Campos et al. (2016)					X	
	Laget et al. (2008)	X					

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
	Moral et al. (2016)			X			
	Ohana-Levi, N., et al. (2022)				X	X	X
	Ramos et al. (2012)	X					X
	Yang et al. (2022b)	X					
Precipitation intensity	Di Carlos et al. (2019)	X					X
Precipitation concentration index	Di Carlos et al. (2019)	X					
Precipitation coefficient	Zaldea et al. (2021)	X					
Indices that focus on combining temperature/GDDs with Precipitation measures							
Hydrothermic index	Heydari and Movaghari (2021)	X					
	Iliescu, M., et al. (2019)	X					
	Lorenzo, M. N., et al. (2016).						
De Martonne aridity index (IDM)	Zaldea et al. (2021)	X					
	Heydari and Movaghari (2021)	X					X
The vine bioclimatic index	Zaldea et al. (2021)	X					
The oenoclimate aptitude index	Zaldea et al. (2021)	X					

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
Evapotranspiration/PET only							
	Camps & Ramos (2012)				X		X
	Cancelas et al., (2016)			X			
	Colak and Yazar (2017					X	X
	Duchene and Schneider (2005)	X					
	Fraga and Santos (2018)			X	X		
	Jagosz, B., et al. (2022).		X			X	
	Laget, F., et al. (2008).	X					
	Kapur, B., et al. (2010).	x					X
	Mandic, M. V., et al. (2022).	X					
	Martinez de Toda & Ramos (2019)			X			
Integrating precipitation data and other factors aside from temperature or direct ET calculations							
Water balance model (Rainfall –ET) also reference to as P=Etc index or climate water deficit (CWD)	Duchene and Schneider (2005)	X					
	Hofmann et al. (2022)	X					
	Kapur, B., et al. (2010).	x					X

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
	Ramos and Martinez Toda (2019)						X
	Ramos and Martinez Toda (2020)	X		X			X
	Ramos and Martinez Toda (2022)			X			X
Dryness Index	Aparecido et al (2018)				X		
	Cancelas et al., (2016)			X			
	Fraga et al. (2014)			X			
	Mandic, M. V., et al. (2022).	X					
	Martins et al. (2021)	X					
	Trbic et al. (2020)	X		X			
	Teslić et al. (2017)	X			x		
Standardized Precipitation Evapotranspiration Index (SPEI)	Araujo et al. (2016)			X			
	Sántillan, D., et al. (2019).	X					
Water Deficit Stress Index (WDSI)	Bois et al. (2020)			X			
Water stress index	Gaudin et al 2014						x
CWSI	Bonfante et al. (2015)			X			
	Colak and Yazar (2017					X	X

Index	Article	Climate change (past and present)	Site choice	Terroir zoning/ spatial variability at local scale	General seasonal and site characterisation/ inter-annual climate variability	Irrigation decisions	Yield or quality relationships
	Yang et al. (2022a)						X
	Yang et al. (2022b)	X					
Palmer Drought Severity Index	Di Carlo et al. (2019)	X					
Precipitation deficit probability	Jagosz, B., et al. (2020).					x	
Drought stress days	Hofmann et al. (2022)	X					
Rausch model index integration	Moral et al. (2016)				X		
Water productivity indices	Cancelas et al. (2016)			X			
Available soil water	Ramos et al. (2020)						X