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Research Article

Weather Variables for Within-Vineyard Awareness of Botrytis Risk

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Background and Aims. Botrytis bunch rot (BBR) in cool temperate climates is a key constraint to the consistent supply of grapes to winery specifications. BBR severities have been correlated with specific environmental conditions; however, data-driven applications intended to support crop protection decisions are restricted in access and/or of unknown commercial value. The aims of this study were to evaluate variables providing within-vineyard awareness of BBR risk in Riesling vines. *Methods and Results*. Descriptors of BBR epidemics from eight site years, 2009–2014, were developed for vine areas of ~0.5 ha within two regions of Tasmania with different climates. Two variables using the daily Bacchus index, from crop stage E-L 19 to E-L 31 or 34, accounted for >80% of the variance in the final mean BBR severity. A BBR risk index (BBR-I), incorporating the mean daily Bacchus index from E-L 19 to E-L 31 and the median daily vapour pressure deficit of air at 15 : 00 during the late-season interval, accounted for up to 99.5% of the variance in the final mean BBR severity. The late-season interval (days) or median daily RH (%) at 15:00 in the same period accounted for 86.4 or 83.3% of the variance. Spatial variability of BBR severity mapped in 4.8 ha of Sauvignon Blanc in 2018-19 confirmed the need to apply BBR risk indicators at an appropriate spatial scale. *Conclusions*. Environmental variables with biological relevance served as indicators of BBR risk at the study sites and have the potential to discriminate BBR risk among production regions in Tasmania. *Significance of the Study*. Study findings are expected to support the development of applications that raise awareness of BBR risk at an appropriate spatial scale for in-season adaption of crop protection, diagnosis of crop protection efficacy, and/or site selection decisions. Accompanying formulae with sample data in Microsoft® Excel will support transitions to automated data analyses.

1. Introduction

Botrytis bunch rot (BBR), caused by *Botrytis cinerea*, contributes to the recurring loss of grape yield and wine quality in cool temperate regions worldwide [1]. *B. cinerea* infection causes oxidation, off flavour, and other biochemical changes in wine [2]. Many wineries in Australia and New Zealand set a threshold for botrytis-affected grapes, above which a price penalty or crop rejection may occur [3]. The threshold varies between wineries and is estimated to be from 1 to 12% of berries per bunch with visible symptoms [3]. Lower tolerance of fruit with visible BBR may be applied to some wine styles such as sparkling wine or grapes used to make a dry style of Riesling wine.

Tasmania, an island state in Australia with a cool maritime climate, has an expanding winegrape sector. When seasonal conditions are highly favourable for BBR, the cost to producers in Tasmania of crop and juice loss, and additional labour and processing costs, has been estimated by the first author to be more than 30% of the processed value of wine (AUD123 million in 2020-21, Tasmanian Government) [4]. Crop losses alone are consistent with estimated district losses for cool climate regions of Australia approaching 30% every 3-4 years on average [5]. Therefore, BBR constrains a consistent and adequate supply of quality grapes needed to sustain and grow premium and ultra-premium wine brands.

Even though BBR appears relatively late in the growing season, infection may have established as early as the onset of

flowering [6, 7], with subsequent infections potentially accumulating throughout fruit development [1, 8, 9]. Therefore, monitoring of factors affecting disease development should occur between the beginning of capfall (modified Eichorn–Lorenz (E-L) stage 19) [10] and the time until grapes are ready to be harvested for winemaking.

Identification of crop and environmental variables relevant to the assessment of BBR risk at any given production site can be aided by knowledge of the mechanisms of *B. cinerea* infection and/or factors known to limit or promote the development of disease symptoms. For example, the microclimate in dense canopies is characterised by reduced wind speed, increased duration of surface wetness, and increased relative humidity; these environmental variables are also likely associated with the development of BBR [11, 12]. Differences in bunch and berry characteristics between grapevine cultivars and clones can also influence BBR severity at harvest. These include bunch compactness [13, 14], berry cuticle thickness [15, 16], and the amount of senescent floral debris trapped in grape bunches as a potential source of *B. cinerea* inoculum [17, 18].

Studies describing environmental conditions favouring the germination of *B. cinerea* conidia [19–21] have formed the basis for weather-based indices such as the Bacchus index (BI), an algorithm incorporating surface wetness duration and temperature [22]. Calculation of the BI for any given hour of surface wetness results in an infection risk increment that is the highest when the average hourly temperature is close to 20°C. This putative optimum temperature is consistent with the findings of Ciliberti et al. [23] who observed 100% incidence of infection on detached sections of inflorescences at 50% capfall that had been inoculated with *B. cinerea* conidia and incubated in moist Petri plates for 24 h at 20°C. Some proprietary digital solutions display a time series graph of an accumulated hourly BI for each period of continuous surface wetness, including those that extend beyond 24 h (see [24]). Even if such information is viewed from flowering onwards, it is not known whether users derive insights of practical value given that infection by *B. cinerea* can occur throughout fruit development.

The BI underpins botrytis decision support (BDS) [25] developed using at least 44 site years of data from cool climate regions in New Zealand (three regions) and Australia (two regions: Tasmania and the Yarra Valley of Victoria). The "Early Model" of BDS predicts the risk of ≥3% mean BBR severity at harvest through a daily accumulation of BI from early capfall (E-L stage 19) which is then superimposed on a threshold line for BBR risk adjusted for each additional crop protection input. The intent of BDS is to provide BBR risk information sufficiently early in the growing season to aid decisions about mid- to late-season crop protection. Access to BDS is limited to producers in New Zealand, and the uptake and value of this application for wine businesses have not yet been reported in the refereed literature.

Hill et al. [26] used 101 site years of data, including those used to develop BDS, for automated analyses that identified relative humidity and surface wetness duration as significant and consistent predictors of ≥3% BBR severity. In practice, relative humidity is a more readily available data stream than surface wetness duration, with sensors for the former routinely present within on-farm weather stations. It is not known if these "moisture" variables are reliable site-specific predictors of ≥3% BBR severity in individual vineyards and/or whether they indicate site-specific weather conditions conducive to BBR development.

Vapour pressure deficit of air (VPD_{air}) is a more accurate environmental descriptor of atmospheric moisture than relative humidity because it represents the difference between the actual water vapour pressure of air and the saturation water vapour pressure at a particular temperature [27]. VPD_{air} has also been associated with biological processes of plant pathogenic fungi such as conidial germination, germ tube growth, and conidial production of *B. cinerea* [28–31]. Thomas et al. [11] demonstrated the importance of evaporative potential, influenced by windspeed, on the development of *B. cinerea*. While VPD_{air} may not be related to the amount of air circulation in the canopy, increasing VPD_{air} increases the atmospheric demand for water [32]. VPD_{air} is thus related, albeit indirectly, to the evaporative potential and how *B. cinerea* senses dryness or moisture in its immediate environment.

VPD_{air} can be calculated using readily available measures of temperature and relative humidity [33]. We hypothesise that patterns of VPD_{air} expressed during the grape ripening period from véraison (E-L stage 34) to preharvest assessment of BBR severity will discriminate late-season conditions conducive to BBR development relative to locations or seasons that remain relatively dry during berry ripening. Such information may be useful for selecting production sites or varieties for new plantings and/or to aid postseason interpretation of crop protection efficacy.

The primary objective of this study was to evaluate weather variables based on the BI and VPD_{air} as indicators of BBR risk in ~0.5 ha areas of Riesling vines within commercially managed vineyards in two regions of Tasmania with different climates. Importantly, it was not the aim of this study to predict a numerical value of BBR severity at harvest because crop and management factors also influence BBR severity to varying degrees within and among sites. Rather, the goal was situational awareness of BBR risk at a given site relative to other sites or seasons, especially when integrated with a producer's knowledge of other factors contributing to BBR severity. To this end, estimates of BBR severity in this study intentionally reflect and embrace variation in viticultural practices in use in the study region and encompass entire vineyard blocks in which BBR severity may be spatially variable [34, 35]. A new weather-based index with the potential to enhance situational awareness of BBR risk is proposed, and its application is discussed. Access is provided to study data and formulae with sample data in Microsoft® Excel spreadsheets to assist broader applications.

The second objective of this study was to explore the importance of applying weather-based information at an appropriate spatial scale by describing spatial variability in the mean BBR severity in Sauvignon Blanc vines planted at a site with variable elevation. Sauvignon Blanc, like Riesling,

is a white variety of *V. vinifera* with relatively thin-skinned fruit and compact bunches that are prone to developing severe BBR.

2. Methods

2.1. Study Sites and Climate. Data were sampled in the years 2009–2014 from eight sites of *Vitis vinifera* cultivar Riesling and from one site of the cultivar Sauvignon Blanc in 2018-19, in vineyards in the localities of Kayena (Kay) and Campania (CP) in the Tamar Valley and Coal River Valley of Tasmania. Each Riesling site was an area of vines of approximately 0.5 ha, referred to as a vineyard block, surrounded by or adjacent to other areas of vines. This area of vines was managed uniformly by the commercial operator according to their normal viticultural practices (Table S1). The Sauvignon Blanc site comprised a total area of 4.8 ha managed uniformly but divided into five contiguous or adjacent areas. Each of the five areas is also referred to as a vineyard block for ease of reference. All the vines had shoots positioned vertically. Row and vine spacings were 2.4 m × 1.5 m (Kay) or 2.5 m × 1.2 m (CP) for Riesling site years and 3 m × 1.5 m for Sauvignon Blanc.

Climate descriptors for the localities of Kay and CP were sourced from climate services for agriculture [36]. CP in south-eastern Tasmania is cooler on average than Kay in northern Tasmania (Table 1). It also has lower potential evapotranspiration (noncrop specific ETo) on average during summer and autumn (Table 1) and less total rainfall on average during the growing and nongrowing seasons: 317 and 227 mm for Campania and 377 and 439 mm for Kayena from October to April and May to September.

2.2. Environmental Data and Weather Variables. Selection and calculation of 12 weather variables presented in the Results section were guided, in part, by previous trans-Tasman research in climates relevant to Tasmanian production regions [37], including the study of Beresford et al. [38] who explored variables such as the mean daily maximum air temperature and mean BI from flowering to prebunch closure, an interval that was sufficiently early in crop development to apply information about weather conditions for adaptation of mid- to late-season crop protection. Postvéraison environmental conditions were also of interest in the current study; hence, the late-season interval was defined as the number of days between crop stage E-L 34 and the date of the final assessment of BBR severity.

Sensor data refer to raw data for the following environmental variables: air temperature, relative humidity, surface moisture (leaf wetness) duration, and rainfall. These data were used to calculate the weather-related variables described in this study. From 2009 to 2013, all environmental sensors were positioned 1.2 m above ground level. Tiny Tag data loggers measuring air temperature and relative humidity (Gemini Data Loggers, UK, sourced from Hastings Data Loggers Port Macquarie, Australia) were housed within a mini-Stevenson screen. A leaf wetness sensor (Campbell Scientific, Inc., Utah, USA) was set at an angle of 10° to the horizontal to prevent water pooling. A tipping bucket rain gauge was set to measure each 0.2 mm of rainfall. In 2013-14, Campbell Scientific sensors were positioned similarly according to the description of Evans et al. [39]. In 2018-19, sensor data were sourced from a weather station maintained on-site by the cooperating vineyard. In all cases, sensors were positioned on a vineyard headland and in a way that avoided the influence of buildings, vines, and/or spray deposits.

The sampling frequency for sensor data—the interval between observed results from sensors—was 10–15 min. Data were averaged across a sampling period; for example, if the sampling frequency was 15 min, then the average air temperature (observed result) at 1:00 was the average of data available in the period 00:45 to 00:59. Hourly averages were calculated from observed results with hourly statistics calculated in the hour prior to the reported time. For example, an hourly BI reported at 10:00 was calculated using data from 9:00 to 9:59. Unless specified otherwise, daily values were the derived statistics (e.g., maximum, sum, and mean) of all observed results for the previous 24 h reported at 9:00 each day.

Time fraction wet (TFW) was defined as the proportion of the sampling frequency when the leaf wetness sensor was wet. For Campbell Scientific sensors, TFW is an observed result representing continuous values. If the hourly average TFW (av_TFW) was ≥0.5, then the hour was considered "wet". If av_TFW < 0.5, then the hour was considered "dry." When relative humidity (RH) was used to estimate surface moisture duration, an hour with an average RH (av_RH) > 95% was classified as "wet." BI was calculated using the average temperature (T_{av}) for each wet hour:

$$\mathrm{BI} = \frac{1}{\left(84.37 - \left(7.238^{*} T_{av}\right) + \left(0.1856^{*} T_{av}^{2}\right)\right)}. \quad (1)$$

Equation (1) is the inverse of the equation reported by Kim et al. [22]. The BI used in data analyses incorporated a "dry-out" period; that is, for any given hour, the hourly BI was calculated if av_TFW was ≥0.5 (or av_RH was >95%) or if any of the previous 4 h were classified as wet.

The daily BI is the sum of the hourly BIs for the previous 24 h reported at 9:00 each day. Daily BIs were accumulated from the estimated date of 5% capfall (E-L 19, early flowering) until the estimated date of véraison (E-L 34) to identify differences among study sites in the temporal progression of this weather variable prior to fruit ripening. The average daily BI prevéraison was calculated as follows:

$$\mathrm{BI}_{\mathrm{mean}} = \frac{\sum\left(\text{daily BI}_{\mathrm{i}} > 0\right)}{n}, \quad (2)$$

where n is the number of days between the estimated dates of E-L 19 and E-L 31 (prebunch closure) when daily $\mathrm{BI}_i > 0$.

Vapour pressure deficit (VPD) of the air at 15:00 on any given day was calculated as follows:

$$\mathrm{VPD}_{\mathrm{air}}\,(\mathrm{kPa}) = \frac{(es - e)}{1000}, \quad (3)$$

Table 1: Climate variables for the localities of Campania (CP) and Kayena (Kay) and deviation from recent historical averages (in parentheses), 1991–2020.

CSA locality	Season	Mean growing season temperature (°C) October to April	Growing degree days (GDD, 10°C base temperature) October to April	Potential ETo[a] December to February (summer)	Potential ETo[a] March to May (autumn)
CP	2009-10	14.2 (−0.4)	904 (−95)	429 (−37)	221 (13)
CP	2010-11	15.0 (0.4)	1075 (76)	469 (3)	196 (−12)
CP	2011-12	15.2 (0.6)	1112 (113)	497 (31)	205 (−3)
CP	2012-13	14.7 (0.1)	1012 (12)	486 (20)	230 (22)
CP	2013-14	14.4 (−0.2)	931 (−68)	455 (−11)	216 (8)
Kay	2009-10	15.4 (−0.3)	1146 (−57)	450 (−40)	230 (4)
Kay	2012-13	15.8 (0.1)	1225 (22)	508 (18)	246 (20)
Kay	2018-19	15.4 (−0.3)	1144 (−59)	476 (−14)	226 (0)

[a]Evapotranspiration (non-crop specific). Data sourced from Climate Services for Agriculture (CSA) [36].

where $es = 610.78\exp[(17.2693882T)/(237.3 + T)]$ and $e = (\mathrm{RH} \times es)/100$, and T and RH are temperature and relative humidity at 15:00 each day [33]. The median $\mathrm{VPD}_{\mathrm{air}}$ ($\mathrm{VPD}_{\mathrm{median}}$) was the median of the daily values for the late-season interval.

The selection of 15:00 for calculating $\mathrm{VPD}_{\mathrm{air}}$ was based on known diurnal trends in VPD [40], whereby $\mathrm{VPD}_{\mathrm{air}}$ is close to the maximum at this time of day. Moreover, data for T and RH at 15:00 are readily available from the network of standardised weather stations across Australia [41], thus allowing meaningful comparison of $\mathrm{VPD}_{\mathrm{air}}$ among locations. From a grape pathology perspective, English et al. [12] found that windspeeds in the afternoon and evening discriminated the microclimate in a canopy in which leaves had been removed from the one where no leaves had been removed. This variable provided greater discrimination between the two canopies than variables such as temperature, vapor pressure, $\mathrm{VPD}_{\mathrm{air}}$, and surface wetness duration. As highlighted in the Introduction, there is a relationship between $\mathrm{VPD}_{\mathrm{air}}$ and evaporative potential, which in turn is influenced by windspeed.

VPD was also calculated for the scenario where there is a 2°C difference between the temperature of the leaf or fruit surface and that of the air. The selection of a 2°C differential was based on multiple observations of the second author who used an infrared thermometer (Bosch Professional GIS 1000C, Robert Bosch (Australia) Pty Ltd.) in thermal bridge mode to compare leaf or bunch temperature with air temperature during commercial winegrape production. In this scenario, $es = 610.78\exp\,[(17.2693882(T - 2)/(237.3 + (T - 2)]$.

A BBR index (BBR-I) for any given site year was formulated by integrating $\mathrm{VPD}_{\mathrm{median}}$ and $\mathrm{BI}_{\mathrm{mean}}$, calculated using wet periods defined by surface wetness duration or relative humidity as follows:

$$\mathrm{BBR-I} = \left(\frac{\mathrm{BI}_{\mathrm{mean}}\mathrm{observed}}{\mathrm{BI}_{\mathrm{mean}}\mathrm{Kay\ 2010}}\right) + \left[\left(\mathrm{VPD}_{\mathrm{median}}\mathrm{Kay\ 2010}\right) - \left(\mathrm{VPD}_{\mathrm{median}}\mathrm{observed} - \mathrm{VPD}_{\mathrm{median}}\mathrm{Kay\ 2010}\right)\right]. \quad (4)$$

In equation (4), Kay 2010 is Kay vineyard 1, block 1 in 2009-10 with means and medians that were associated with the most severe BBR epidemic observed during this study and, arguably, in any season in Riesling vines in Tasmania. Therefore, the values of BBR-I for any other site year should, in theory, be lower than the Kay 2010 reference value of BBR-I.

2.3. Crop Protection, Phenology, and Disease Assessment. The approach taken in this study was to assess the mean BBR severity per vineyard block in which crop protection had been applied according to normal vineyard practices. The BBR severity per vineyard block will reflect those viticultural practices and may be different from values derived from nontreated, small, replicated research plots and experimental vineyards used in previous studies [26, 42]. That is, crop protection was considered an inherent attribute of each site, along with other viticultural practices employed.

Fungicides registered for BBR were applied using commercial practices at key crop stages before véraison (E-L 34) [10]. Crop protection inputs for Riesling vines, except for site year CP 1-1 2009-10 (data unavailable), are described in the Supplementary Materials (Table S1). CP sites 1-1 and 2-1 in 2013-14 were the only sites to receive an application for iprodione from mid- to late February. Leaves were removed manually mid-season at three sites. Grape bunches with severe grey mould were removed by vineyard workers before the final disease assessment at CP site 1-1 in 2010-11, presumably to reduce BBR severity in grape bunches remaining on the vine before the harvest and winemaking. This action likely resulted in an underestimate of the mean BBR. Hence, these data were not included in subsequent analyses.

Canopy vigour and crop load were categorised subjectively by the cooperating growers as low, medium, or high based on their experience of the historical performance of the production site. These common viticultural descriptors were used to check if the study sites encompassed the range of canopy attributes likely to be encountered in the region. Cooperating vineyard managers also shared insights on factors contributing to BBR severity at each production site.

The sampling unit for BBR assessment in Riesling vines was a panel of four to six vines from which 10 bunches were sampled arbitrarily on one side of the panel, and another 10 bunches were sampled from the panel directly opposite in the adjacent row, that is, the two sides of the opposite panels comprised one panel or sampling location. The grid sampling strategy described by Evans [43] was then applied to a minimum of 20 panels across a representative area of approximately 0.5 ha of vines. The two end rows of a block and the first two panels at either end of a row were not sampled to avoid edge effects. For this study, 20–23 panels were sampled per site by walking along four to seven rows, each separated by up to four rows. Typically, every fifth panel was sampled per row. This sampling regime was expected to provide a reliable estimate of the mean BBR severity based on reported values of the standard error to mean ratio (%) for mean BBR severities of 0.4–7.7% in Riesling vines grown in Tasmania [43]. BBR severity was assessed at the same sampling locations 2–4 times in the preharvest period with the final assessment within the week before the commercial harvest date unless indicated otherwise.

BBR severity in Sauvignon Blanc vines was assessed 2 weeks before harvest in 2019 primarily to ascertain the spatial structure of BBR severity across 5 blocks of vines with a total area of 4.8 ha. A total of 140 vines were sampled in a regular grid array across 4.8 ha with 15% of the vines reassigned to vines that were adjacent to other sample vines to enhance short-range modelling of the spatial structure of the measured data . For each sample vine, 10 bunches were selected arbitrarily to assess BBR severity per bunch. BBR severity per vine was calculated from the average BBR severity of $n = 10$ bunches.

The severity of BBR for each bunch was assessed visually with the aid of a standard area diagram as the percentage surface area of exposed berry tissue with BBR symptoms [45]. Disease assessors varied among site years; however, all were trained and assessed for consistency using methods like those described for Bunch Rot Assessment Trainer [45].

Total soluble solids (TSS) are a reliable marker of the progress of grape berry ripening and can be measured readily in the field using a digital refractometer [46]. In this study, the TSS of berry juice from Riesling vines was used to indicate the stage of berry ripening in relation to the timing of the BBR epidemic. TSS was estimated by sampling up to 100 individual berries, one berry each from five bunches on each of the 20 vines in the rows that were used to estimate BBR severity. Berries were squashed inside a polythene bag and the juice filtered through a coarse mesh before measuring the °Brix with the aid of a digital refractometer (PAL-1™, Atago, Japan). The average °Brix was calculated from a minimum of three 100-berry samples.

2.4. Data Analyses. Temporal progression of mean BBR severity per vineyard block was modelled for site years listed in Table 2, each with at least three preharvest disease assessments. Modelling involved transforming mean BBR severity (%) to a logit prior to linear regression against the date of assessment, expressed as the days from January 1900 [47]. The slope of the linear model was the epidemic rate, which was also used to estimate the date for 3% BBR severity, the disease severity threshold used in the models of Beresford et al. [25]. Linear regression was also used to estimate the date for 20°Brix for grape juice for site years with at least three assessments of TSS (Table 2). The estimated date for 20°Brix was estimated by interpolation for one site year that had two assessments of TSS (Table 2).

Associations between the mean BBR severity (%) and the variables listed in the headings of Tables 3 and 4 were investigated using Pearson's correlation coefficient and, where appropriate, by linear regression. Slopes and adjusted R^2 values of linear regression were calculated with the aid of a Microsoft® Excel function. Linear regression to determine the slope of the accumulated daily BI did not include data for consecutive dates representing repetition of the maximum accumulated daily BI once the maximum value had been recorded. The polynomial model describing the relationship between the final mean BBR severity and BBR-I was calculated with the aid of the LINEST function in Microsoft® Excel.

3. Results

Seasonal deviations from historical averages revealed that locality Kay in 2009-10 and 2018-19, and CP in 2009-10 and 2013-14 were cooler than average with a lower potential ETo in summer (December to February) than in other site years of the study (Table 1). CP in 2011-12 had higher potential ETo than average in summer and near average ETo in autumn (March to May), whereas CP and Kay in 2012-13 had higher potential ETo than average in both summer and autumn.

Epidemics of BBR on Riesling vines varied in their timing (Figures 1(a)–1(f)) and rate of disease progression (Table 2). Final BBR severities ranged from 1.5 to 95% (Figure 2), with values at CP sites numerically lower than those observed at Kay sites 1-1 and 1-2 (Table 2). The estimated date of 20° Brix of grape juice was beyond that for 3% BBR severity for the five site years of available data (Table 2), indicating that commercially significant levels of BBR likely occurred prior to optimum harvest dates for dry or semidry styles of Riesling wine. Vineyard managers reported ≥3% BBR severity in the previous growing season at five of the six site years where this information was available (Table 2). In this production context, targeted crop protection (Table S1) did not prevent BBR development among site years with variable canopy vigour and crop load (Table 2).

Time was a factor associated with final mean BBR severity. The late-season interval (t, days) accounted for 86.4% of the variance in the final mean BBR severity (y), according to the equation $y = 2.233t - 100.33$, $n = 6$. Weather variables derived from temperature, surface wetness duration, and

Table 2: Descriptors of each epidemic of botrytis bunch rot (BBR) in relation to ripening of Riesling vines.

Locality, vineyard-vineyard-block	Season	Canopy vigour and crop load (vigour/load)	Previous season BBR severity	Date of 5% capfall	Estimated date for 3% BBR severity[b]	Estimated date for 20°Brix of grape juice[b]	Date of final assessment for BBR severity	Late season interval[f] (days)	Final mean BBR severity (%) ± standard error (number of bunches)	Epidemic rate[i]
CP 1-1	2009-10	Not recorded	No data	Dec 2[a]	Apr 2	No data	Apr 9	(53)[g]	7.69 ± 0.60 (500)	0.1365
CP 1-1	2010-11	Medium/ medium	≥3%	Dec 8	Apr 3	Apr 21	Apr 19	77	10.5[h] ± 0.85 (400)	0.1276
CP 1-1	2011-12	Medium/not recorded	≥3%	Dec 4	Mar 13	Mar 20	Mar 27	46	10.9 ± 0.71 (400)	No data
CP 1-1	2012-13	Medium/ medium	≥3%	Dec 4	Mar 11	Mar 22[d]	Apr 2	59	23.0 ± 0.86 (400)	No data
CP 1-1	2013-14	Low/low	≥3%	Dec 10	Mar 30	No data	Mar 31	44	4.7 ± 0.58 (460)	0.2066
CP 2-1	2013-14	High/low	<3%	Dec 5	May 15[c]	No data	Apr 8[e]	48	1.5 ± 0.34 (420)	No data
Kay 1-1	2009-10	Medium/not recorded	No data	Dec 6	Mar 3	Apr 4	Apr 26	80	95.2 ± 0.34 (400)	0.1242
Kay 1-2	2012-13	Medium/ medium	≥3%	Dec 10	Mar 22	Apr 2	Apr 23	70	37.7 ± 1.37 (400)	0.1001

[a]Default value (actual date not recorded). [b]From linear regression where $n = 3$ or 4. [c]From linear interpolation because $n = 2$. [d]Beyond harvest date. [e]More than 5 days before harvest date. [f]Number of days between véraison and final assessment of BBR severity; [g]15 Feb used as a default value for veraision. [h]Likely an underestimate or inaccurate because bunches with severe mould were remove. [i]Using the method of Beresford et al. [47]; $n = 3$ or 4 and R^2 was 0.91–0.98.

Table 3: In-season weather variables derived from temperature and/or surface wetness duration with a 4 h dryout period. There are no data for CP vineyard 2-1.

Locality, vineyard-vineyard-block	Year of grape harvest	Mean BBR severity (%) at final assessment	Mean daily maximum air temperature from E-L 19 to E-L 31	Mean wetness duration[b] (h) for days with a BI > 0 from E-L 19 to E-L 31	Mean BI for days with a BI > 0 from E-L 19 to E-L 31	Accumulated daily BI (Figures 1(a)–1(f))		
						E-L 19 to E-L 34	Slope of linear regression with time[c]: E-L 19 to E-L 34	E-L 19 to estimated date of 3% botrytis severity
CP 1-1	2010	7.7	24.9	8.44	0.38	27	0.321	48
CP 1-1	2011	10.5[a]	24.0	10.7	0.52	30	0.580	67
CP 1-1	2012	10.9	25.1	10.3	0.53	32	0.433	44
CP 1-1	2013	23.0	26.3	7.89	0.40	19	0.265	31
CP 1-1	2014	4.7	22.3	8.67	0.41	26	0.372	45
Kay 1-1	2010	95.2	22.3	12.1	0.66	40	0.644	57
Kay 1-2	2013	37.7	23.4	9.79	0.52	31	0.474	55
		Correlation coefficient[d]	−0.416	0.787	0.840	0.717	0.823	0.628

[a]Likely an underestimate because bunches with severe mould were removed by vineyard workers. [b]Using the variable wet_TFW_dryout (4 h dryout period). [c]Range of R^2: 0.985–0.999. [d]Pearson's coefficient excluding data for CP site 1 in 2010 (E-L dates imprecise) and 2011 (BBR severity likely underestimated); $n = 5$.

Table 4: In-season weather variables derived using temperature, relative humidity, and rainfall and associations with final mean BBR severity. VPD = vapour pressure deficit calculated from temperature and relative humidity (RH) [33].

Locality, vineyard-vineyard-block	Year of grape harvest	Mean BBR severity (%) at final assessment	Cumulative rainfall days ≥1 mm, March 1 to final botrytis assessment	Median daily RH (%) at 15:00: E-L 34 to final BBR assessment	VPD_{air} (kPa) at 15:00 each day: E-L 34 to final BBR assessment			
					Median VPD_{air}	Median VPD with 2°C differential[b]	Slope of linear regression[c] for accumulated daily values	Accumulated daily values: véraison to estimated date of 3% botrytis severity
CP 1-1	2010	7.7	8	47.2	1.45	1.13	1.564	75
CP 1-1	2011	10.5[a]	12	53.4	1.16	0.85	1.212	79
CP 1-1	2012	10.9	8	53.9	1.28	0.98	1.396	48
CP 1-1	2013	23.0	5	45.1	1.67	1.32	1.834	76
CP 1-1	2014	4.7	3	43.2	1.47	1.18	1.582	64
CP 2-1	2014	1.5	5	43.8	1.28	1.02	1.465	No data
Kay 1-1	2010	95.2	6	63.2	0.96	0.66	0.959	31
Kay 1-2	2013	37.7	9	58.6	1.06	0.73	1.056	53
Correlation coefficient[d]			0.250	0.833	−0.675	−0.717	−0.721	−0.735

[a]Likely an underestimate because bunches with severe mould were removed by vineyard workers. [b]Calculation accounts for a 2°C difference between the temperature of the leaf or fruit surface and that of the air. [c]Range of R^2: 0.975–0.995. [d]Pearson's coefficient excluding data for Campania site 1 in 2010 (E-L dates imprecise) and 2011 (BBR severity likely underestimated); $n = 5$ or 6.

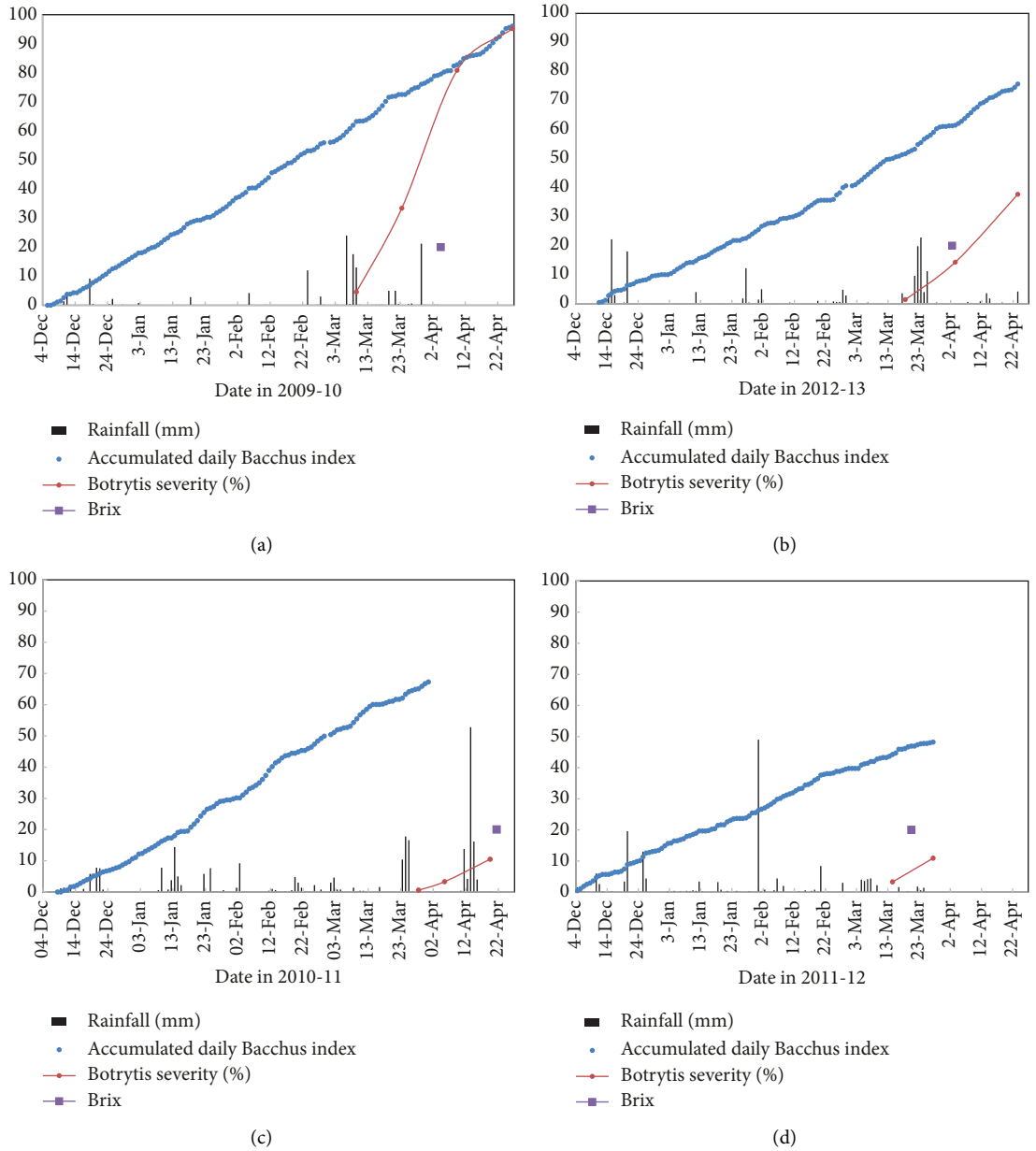

Figure 1: Continued.

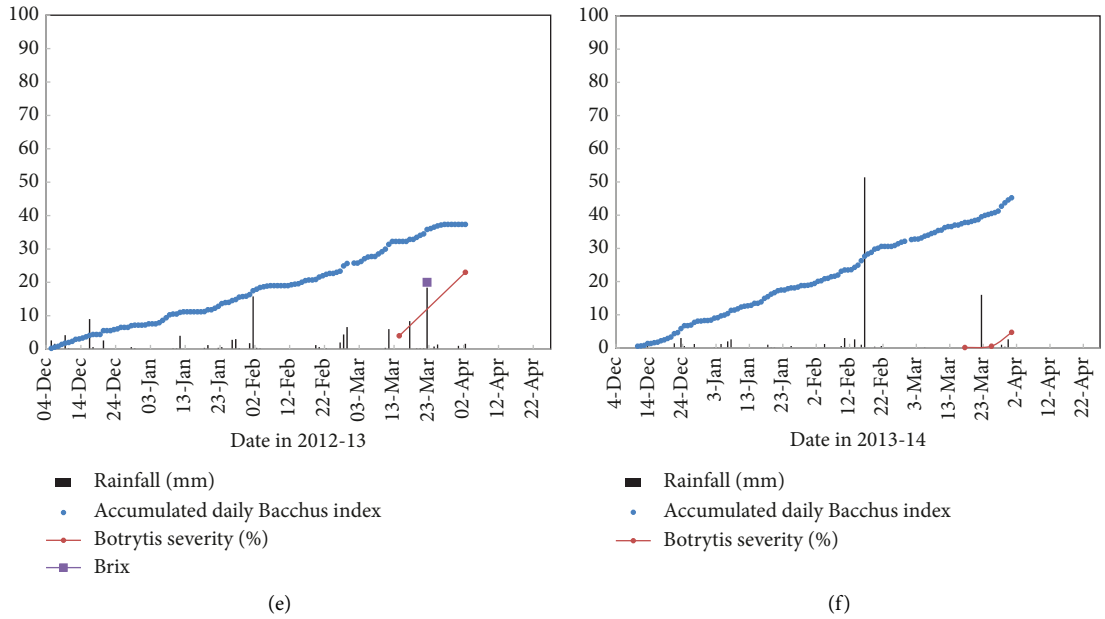

Figure 1: Accumulated daily Bacchus index, integrating temperature and surface wetness duration from E-L 19 (5% capfall), total daily rainfall, mean botrytis bunch rot (BBR) severity (%), and where available, the estimated date of 20°Brix of grape juice at (a) Kay, 2009-10, (b) Kay, 2012-13, (c) CP 1, 2010-11 (no surface wetness data from Mar 31 onwards), (d) CP 1, 2011-12, (e) CP 1, 2012-13, and (f) CP 1, 2013-14.

Figure 2: Symptoms of botrytis bunch rot on Riesling grapes at Kay site 1-1 on (a) 23 March 2010, when the mean BBR severity was 33% and on (b) 26 April 2010 when the mean BBR severity was 95% and berries were becoming shrivelled and dehydrated.

relative humidity also resulted in positive or negative trends with final mean BBR severity, with correlation coefficients in the range 0.416–0.840 (Tables 3 and 4). There was a weak positive association with cumulative rainfall days ≥1 mm from March 1 (Table 4).

For the period prior to véraison (E-L 34), two weather variables produced a correlation coefficient higher than 0.8; that is, the BI_{mean} from 5% capfall (E-L 19) to prebunch closure (E-L 31) and the slope of the linear regression of the accumulated daily BI from 5% capfall to véraison (E-L 34) (Table 3). BI_{mean} calculated using av_RH to determine wet hours resulted in a correlation coefficient of 0.537 (data not presented). Temporal accumulation of daily BI values was similar when TFW was determined using av_TFW or av_RH (Figure 3). However, the final value of accumulated daily BI was either higher or lower for av_TFW or av_RH, according to the growing season. The correlation coefficient for mean daily wetness duration using av_TFW for the same period was 0.787 (Table 3) or 0.521 if wet hours were determined using av_RH (data not presented).

For the late-season interval, the median daily RH at 15:00 was 43.2–63.2% and associated positively with final mean BBR severity. VPD_{median} for the late-season interval and the slope of the linear regression for the temporal accumulation of daily VPD_{air} were associated negatively with the final mean BBR severity, with values lower at Kay sites than at CP sites (Table 4). Daily VPD using a 2°C differential revealed a similar spread of values to VPD_{air} in the late-season interval (Figure S1), indicating that VPD_{air} is likely to be a suitable variable for use in a cool climate where the temperature differential between the fruit surface and air is likely to be consistent in the preharvest period.

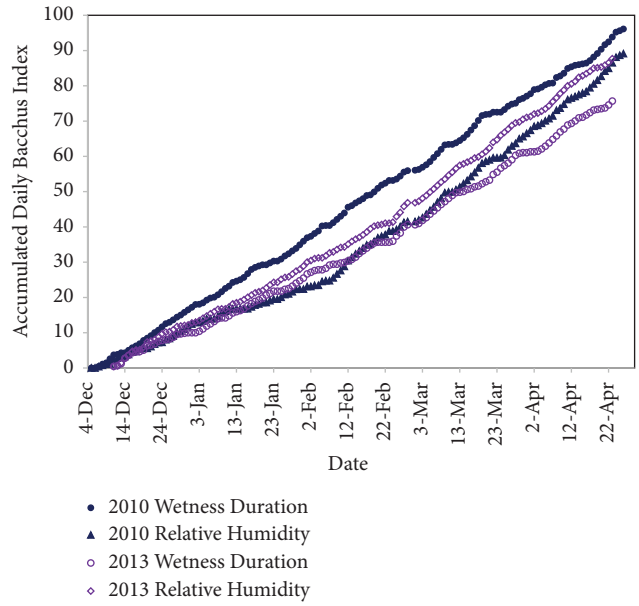

Figure 3: Accumulated daily Bacchus index (BI) based on an hourly BI calculated using the hourly average time fraction wet (wetness duration) or hourly average relative humidity at the Kayena site 1-1 and 1-2 in 2009-10 and 2012-13.

BBR-I (x), calculated using BI_{mean} (from T and av_TFW) and VPD_{median}, accounted for 99.5% of the variance in final mean BBR severity (y) ($n = 5$) (Figure 4(a)). Using this polynomial model, the estimated BBR severity for CP 1-1 in 2009-10 was 5.7%, which is of the same order of magnitude as the observed value of 7.7% (Tables 2–4). BBR-I (x) calculated using av_RH in the calculation of BI_{mean} accounted for a lower percentage of the variance in the final mean BBR severity (y) than for the wet periods defined by av_TFW ($R^2 = 0.81$) (Figure 4(b)). Values of BBR-I < 0.9 (Figure 4) include a site year (CP 1-1 2012-13) with a lower BI_{mean} and higher VPD_{median} relative to other site years while also expressing a final mean BBR severity (23%) that was neither the highest nor lowest observed in this study. In contrast, values of BBR-I > 1.5 were associated with mean BBR severity >37% and conditions where the BI_{mean} was relatively high and the VPD_{median} was relatively low. A model analogous to equation (4) using median daily RH at 15:00 rather than VPD_{median} was developed; however, the model accounted for a lower percentage of variance in final mean BBR severity (92%) when av_TFW was used in the calculation of BI_{mean} (data not presented).

The results of this study pertain to the association between the average BBR severity across defined areas of Riesling vines (~0.5 ha) and environmental conditions based on data from nearby sensors (Table S2 describes the data repository). Figure 5 illustrates the spatial variability in BBR severity across multiple adjacent areas of Sauvignon Blanc vines, collectively 4.8 ha, at site Kay 1–3 in 2018-19. Visually, BBR severity varied with elevation, and each block had a different mean BBR severity [35]; the highest and lowest mean BBR severity per block was 10.1% for K51-1 (Figure 5, bottom left) and 0.6% for K53-2 (Figure 5, top right). Data from the on-vineyard weather station, which was approximately 1 km from this planting of Sauvignon Blanc, revealed a BI_{mean} (using av_TFW) of 0.555 and a VPD_{median} of 1.241, consistent with the values observed for Riesling vines (Tables 3 and 4).

4. Discussion

This study focused on two climatically distinct localities for wine grape production in Tasmania and areas of Riesling vines with a history of BBR. Detailed descriptions of BBR development in vineyard blocks managed commercially revealed a broad range of final mean BBR severities and correlations with in-season weather variables relevant to the biology and epidemiology of *B. cinerea* in winegrapes. BBR epidemics also varied in the timing of the exponential increase, consistent with the findings of Molitor et al. [49] for Riesling vines grown in Germany.

While specific in-season weather conditions were associated with disease development, the late-season interval (days) from véraison accounted for 86% of the variance in final BBR severity among the Riesling sites studied. A model reported by Beresford et al. [38] predicted that a region with >3% mean BBR severity would, on average, have a late-season interval of >41 days, a threshold that was also exceeded at each site year in this study (Table 2). This regional-level trend was thus reflected in the results for individual vineyards reported here. A relatively long late-season interval may also increase the opportunity for rain events in the preharvest period; however, there was a weak association in the current study between the number of days with >1 mm rainfall from March 1 and the final mean BBR severity. Beresford and Hill [24] reported a correlation coefficient of 0.44 for the association between the number of days with rain late in the season and BBR severity near harvest using 44 site years of data. They also noted that this variable was associated positively with the late-season

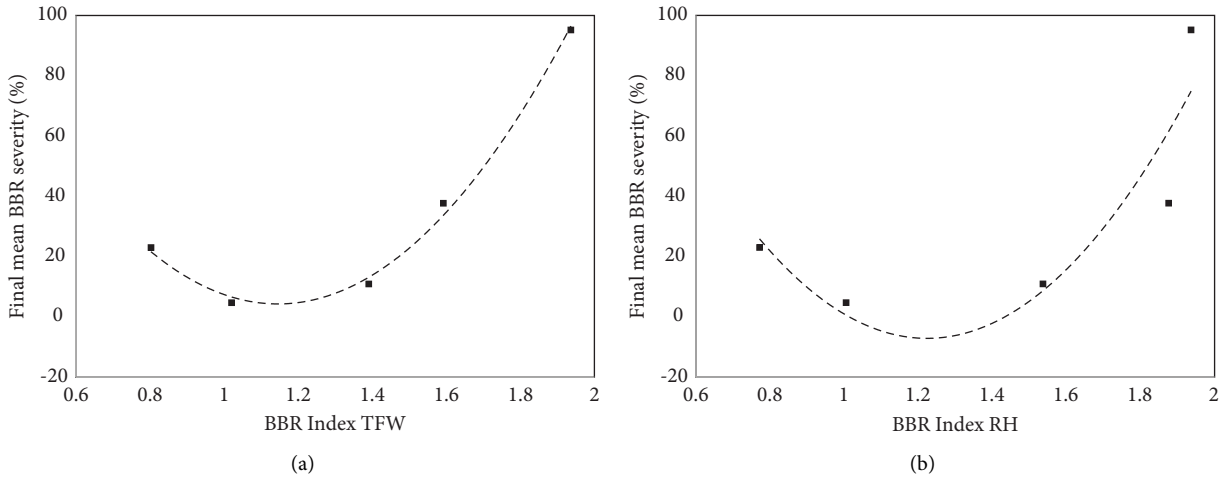

FIGURE 4: Relationship between y = final mean BBR severity (%) and x = a BBR index that integrates late season VPD_{median} and prevéraison BI_{mean} with wet periods defined using (a) hourly average time fraction wet (surface moisture), $y = 147.43x^2 - 338.88x + 197.86$ ($R^2 = 0.995$) or (b) hourly average relative humidity, $y = 161.48x^2 - 395.23x + 234.68$ ($R^2 = 0.81$). Site-years used for the analyses were as follows: Campania site 1 in seasons 2011-12, 2012-13, and 2013-2014 and Kayena sites 1-1 and 1-2 in seasons 2009-10 and 2012-13.

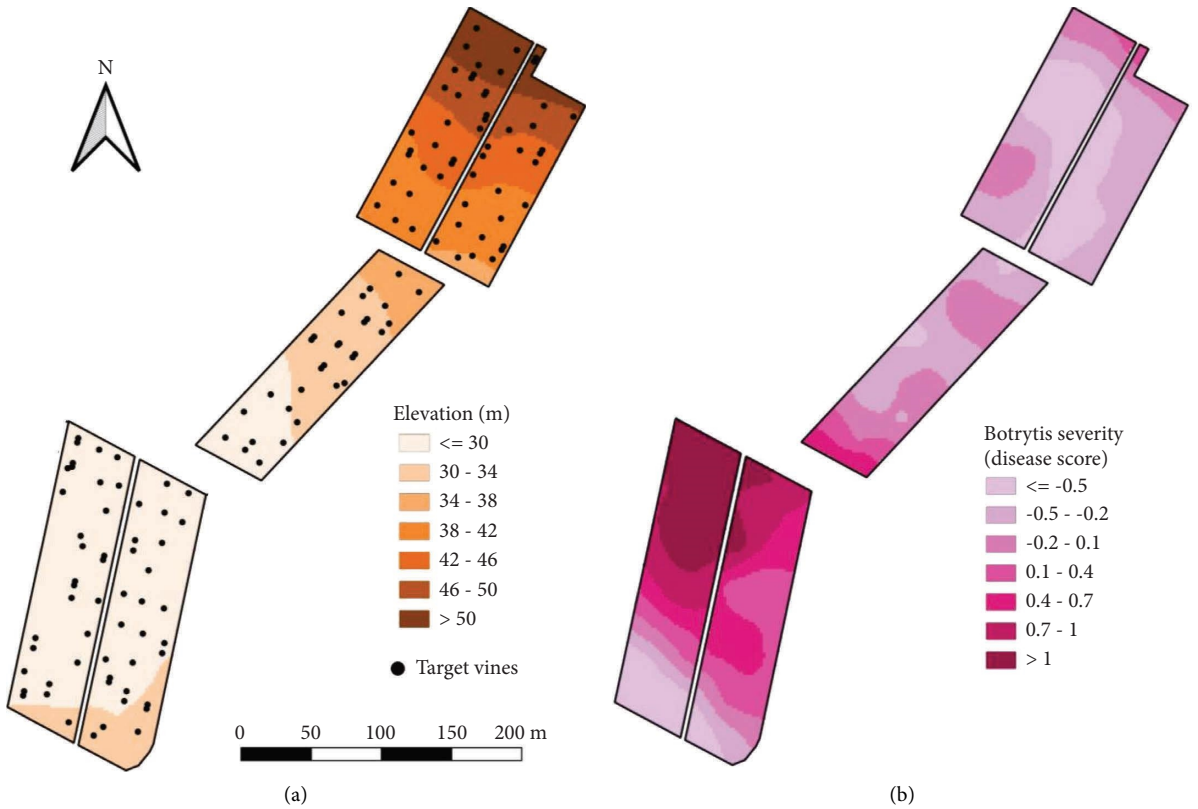

FIGURE 5: Reproduced from Song [43] and adapted with the author's permission, (a) elevation (minimum: 26.6 m maximum: 53.9 m above sea level) and (b) BBR severity (%) on 27 March 2019, 19 days before commercial grape harvest. The five vineyard blocks represent a total of 4.8 ha of Sauvignon blanc vines near Kayena, Tasmania, with the mean BBR severities (%) in ascending order: 0.6, 1.7, 2.9, 5.4, and 10.1 (SE for each mean: 0.002–0.018, n = 25–30). Song [43] sampled each vine (black dot) and transformed data to a disease score prior to kriging using the VESPER tool of precision agriculture tools [48].

interval. A routine association of severe BBR with a late-season interval longer than 40 days at any given site suggests opportunities to manage fruit loads to advance fruit maturity [50, 51], assuming desired fruit composition occurs prior to a BBR severity that would be considered commercially unacceptable.

An explanation for the weak association between late-season rainfall days and final mean BBR severity may relate to BBR epidemiology in the region of this study. If a high proportion of nonsymptomatic latent infections by *B. cinerea* was established prevéraison[8], then the disease symptoms observed at one or more sites in this study may represent pathogen colonisation of grape berries after the fungus emerges from a quiescent state. The preliminary report of Zitter and Wilcox [52] suggests that regrowth of *B. cinerea* from latent infections in potted Chardonnay vines maintained outdoors but sheltered from rain was stimulated by irrigation after véraison and/or by imposing relative humidity (RH) >92% immediately preharvest. Hill et al. [53] used sheltered vines (Sauvignon Blanc) in an experiment designed to test the hypothesis that late-season growth of *B. cinerea*, visible as the 'slip skin' symptoms, is stimulated by an increase in the osmotic potential of the fruit after uptake of water following a rain event. However, the results of their field experiment were inconclusive, partly because the underlying level of latent infection was not quantified. Daily rainfall ≥1 mm is likely to influence VPD_{air} at 15:00, with VPD_{air} known to be associated with biological processes of plant pathogenic fungi [28–31]. Even so, the mechanisms promoting regrowth of latent *B. cinerea* remain obscure.

The most severe epidemic observed in this study (Kay site 1-1) was associated with a relatively rapid rate of disease increase (Figure 1(a)), disease-conducive weather, a relatively high crop load, and a long late-season interval. Six rainfall events ≥1 mm from March 1 may have also slowed the development of berry total soluble solids [54]. Berries with splits or other visible injuries were largely absent at Kay site 1-1, suggesting the symptoms were an expression of accumulated latent infections [8]. In contrast, the vineyard manager at site CP 2 in 2013-14, where mean BBR severity was relatively low at 1.5%, noted that seasonal conditions were conducive to low fruit set and that bunches were smaller and had fewer and smaller berries relative to other seasons. His broad opinion about this site year was that "*bad areas for botrytis are purely environmental*," which may be interpreted to mean that BBR severities were spatially variable and that bunch architecture *per se* did not exacerbate mean BBR severity.

Descriptors of BBR epidemics at site CP 1 over multiple seasons aided comparison of the features of these epidemics. The epidemic in 2013-14 (Figure 1(f)) had nearly double the rate observed in 2010-11 (Figure 1(c)), although it is not known if the stage of berry ripeness influenced differences in this rate parameter. The epidemic in 2013-14 also had a late-season interval that was shorter by 33 days and a lower final BBR severity (Table 2). Climate data (Table 1) revealed that the 2013-14 season was cooler than 2010-11; however, potential associations between deviations from historical climate averages and BBR severity observed among all site years were obscure. The 2013-14 season had fewer cumulative rainfall days ≥1 mm from March 1 (Table 4), and the VPD_{median} was higher (Table 4) than in 2010-11. Unlike 2010-11, iprodione fungicide was applied postvéraison in 2014 (Table S1), a material that would be expected to reduce the epidemic rate (see Figure 3 in [43]). Actual fungicide efficacy at this and other sites was not investigated; however, spray applications can be less effective when spray coverage is poor and/or a fungal population has developed resistance to treatment. Otherwise, both botrytis epidemics had similar locations in time (Figures 1(d) and 1(f)), suggesting that BBR severity near harvest in 2013-14 was associated with the number of days since véraison.

The late-season variable VPD_{median} was investigated because of its potential to be a more biologically meaningful variable than the median daily RH (%) at 15:00. Both variables appear to be indicators of relative BBR risk post-véraison with potential to distinguish localities in Tasmania based on the differences observed between sites CP 1 and those for sites Kay 1-1 and 1-2. This finding might reflect the known requirement of free water for the germination of *B. cinerea* conidia [19]. However, VPD is known to drive grape berry transpiration in cultivars of *V. vinifera* studied to date [55–58]. Associated impacts on fruit water relations [56], fruit ripening and flavour development [58], berry volume and sugar concentrations, and the mechanical resistance of the berry cell wall (reviewed in [59]) are likely to influence fungal penetration of the berry skin and/or colonisation of berry tissues according to available metabolites, including those that inhibit fungal enzymes required for nectrotrophy [60, 61]. Potential associations between VPD, berry physiology, and fungal colonisation might explain why BBR-I calculated using VPD_{median}, rather than median daily RH (%), accounted for a greater proportion of the variance in BBR severity. Colonisation of berries by *B. cinerea* in different environments warrants further investigation to determine if dynamic and complex changes in berry physiology over time can be accounted for.

The focus of this study was situational awareness of relative BBR risk rather than disease prediction; hence, a simple computational approach was applied to biologically meaningful variables for ease of practical application and interpretation. Combining key pre- and post-véraison weather variables into one weather-based index resulted in an empirical polynomial model relating BBR-I to the final mean BBR severity. BBR-I can be calculated easily using a spreadsheet and data from readily available environmental sensors with the option of using relative humidity if data for surface wetness duration are unavailable. The quadratic model (Figure 4) suggests a likely optimum range of the BBR-I, above or below which environmental conditions are more conducive to BBR development. The polynomial response likely reflects complex interactions among weather variables driving BBR severity.

BBR-I should be viewed as a general descriptor of environmental conditions conducive to the development of BBR, alongside information about the late-season interval (days). The latter variable is associated negatively with VPD_{median} which is not surprising given that VPD_{median} is calculated for the late-season interval; hence, care should be taken when interpreting these variables. While values of in-season weather variables associated with BBR severities in Sauvignon Blanc were like those observed in Riesling vines, additional data are needed to validate the applicability of the

study findings to other white varieties of *V. vinifera*. Data for additional climates and seasons are also needed to ascertain the predictive ability of BBR-I while noting that empirical models of this type are generally applied in the regions in which they are developed to account for local climate, disease epidemiology, and crop management practices.

The empirical models for BBR-I are not directly comparable to those of Molitor et al. [42, 49] who used five input variables from study sites in Germany to develop a BBR risk model with a coefficient of determination of 0.63. A key difference between Germany and Tasmania relates to the influence of climate on the duration of flowering phenology [62]. In Tasmania, a protracted flowering period of 2-3 weeks [63] can coincide with multiple periods of surface moisture favouring cohorts of latent infection. Use of environmental conditions between E-L 19 and E-L 31, such as mean daily maximum air temperature (Table 3), is relevant to flowering phenology and fruit set in Australia and New Zealand, with likely flow on effects to berry size, bunch architecture, and grape maturity dynamics [54]. This interval is also sufficiently long to reveal the pattern and slope of the accumulating daily BI, knowledge that could be used to justify a prebunch closure fungicide application at a time when sufficient spray coverage of grape berries is still achievable.

The variation in final mean BBR severity among five colocated blocks of Sauvignon Blanc in this study (Figure 5) highlights the opportunity to develop block-specific models through the accumulation of historical disease and weather data plus integration of features of the land observed to covary with BBR severity. While there was an apparent association between BBR severity and elevation in the 4.8 ha studied, spatial patterns in BBR severity may not be stable among seasons [35]. One can envisage application of automated analyses like those of Hill et al. [26] using data collected at finer spatial scales of resolution as these become easier to access. Even so, spatial patterns of relative BBR risk may be of little use in practice if there is no scope for differential crop protection or management. For now, immediate implementation of the weather variables identified in this study will be facilitated by access to standardised data from a nearby weather station.

Situational awareness of BBR risk necessarily requires that producers draw upon their experiential knowledge to interpret the relative importance of environmental data in relation to crop and management factors affecting in-season disease risk [64]. Such knowledge will then inform decisions about canopy management, in-season adaption of crop protection, and/or advancing harvest dates if feasible. Any change to disease management will depend on vineyard capacities to adapt operations to achieve viticultural goals. Weather-based descriptors of relative BBR risk may also aid interpretation of the performance of existing or alternative disease management tactics under different seasonal conditions. This information may be especially important for biological crop protection products whose efficacy may be weather dependent [65].

Rapid, objective measures of BBR severity via remote sensing are needed to accelerate weather-based modelling efforts and to aid the definition of vineyard areas suitable for their application. Such efforts will require a better understanding of the spatial variability and temporal stability of spatial patterns in BBR severity. Such patterns are moderated by features of the land, vine row orientation, and canopy architecture that in turn influence temperature, relative humidity, surface wetness duration, and wind speed. Recent work to simplify and improve the efficiencies of on-vineyard trials also points to the potential to estimate BBR severity from a single vineyard row that represents most of the variance in this response variable [66]. Metadata and sample data sets from this study should aid standardised implementation of algorithms in digital applications that will benefit in the future from remote sensing of BBR severity and machine learning approaches.

5. Conclusions

Weather conditions associated with BBR development in Tasmanian vineyards can be summarised in biologically relevant variables calculated using readily available sensor data. Routine documentation of the late-season interval and the BBR-I or one of its components, along with estimates of final BBR severity per vineyard block, are likely to build situational awareness of how specific weather or production conditions impact the effectiveness of crop protection. The BBR-I may have predictive value if site-specific algorithms calibrated to data from local environmental sensors are developed for areas of vines defined using knowledge of spatial variability in disease severity. A regional viticultural descriptor that encompasses BBR risk could also aid in the selection of sites and grape varieties for new plantings. Beyond situational awareness, it remains to be seen whether reliable prediction of BBR risk at a desired spatial resolution will be feasible given the many factors influencing BBR severity.

Data Availability

Environmental and disease data used to generate the study results and Excel spreadsheet calculators with sample data have been deposited in the University of Tasmania Research Data Portal (https://rdp.utas.edu.au/metadata/731feb6c-23a4-4363-a30d-d7e1859aa081) [67]. A description of the available data files is provided in the Supplementary Materials (Table S2).Requests for these data will be considered by the corresponding author and will be conditional on appropriate citation in future publications or applications.

Conflicts of Interest

The authors declare there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

The supplementary materials contain a description of crop protection actions at Riesling study sites (Table S1), a description of the Microsoft Excel files in the data repository (Table S2), and box and whisker plots of daily vapour pressure deficits at 15:00 (VPD of the air or with a plant-atmosphere temperature differential) during the late-season interval (Figure S1). (*Supplementary Materials*)

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