Climatic Adaptivity of the Grapevine.

A report compiled for the CRC-NA Project: A.22122014
'Novel Agronomic Practices to Achieve Productive and Profitable Viticulture in Northern Australia'

EXECUTIVE SUMMARY

Successful table grape production in lowland subtropical and tropical regions requires agronomic practices that address the challenges associated with high day and night temperatures and limited seasonal variation in photoperiod. Considerable international experience exists in managing these conditions and is reviewed here to inform the continued refinement of Australian production systems. Viticulture in tropical regions has been practised for centuries and, although often only partially documented in the scientific literature, is supported by a substantial body of practical knowledge and industry experience.

This review documents the climate of Australian table grape production regions and evaluates them in the context of the climates of the foundation viticultural regions of the Levant and Caucasus, together with established production regions in Brazil. For the purposes of broad comparison, these regions are grouped into six climate types. These groups are intended as a practical framework for discussion and do not correspond directly to established climatic classification systems such as Köppen-Geiger.

A separate study regarding pests (Spodoptera litura), cluster caterpillar, has been presented as a case study.

Beyond synthesising existing knowledge, this report identifies opportunities arising from advances in plant science and agronomy that may further improve productivity, production consistency, and resource-use efficiency. Particular attention is given to challenges commonly associated with warm production environments, including flower initiation and development, primary bud necrosis, respiratory losses of photosynthates, and the partitioning of assimilates between fruit production and reserve accumulation.

The review concludes that there is a strong scientific and practical foundation for continued innovation in subtropical and tropical table grape production. It does not prescribe specific management interventions. Rather, it supports the development of targeted, site-based evaluation programs to determine which approaches deliver measurable benefits under Australian production conditions before wider industry adoption is considered. Several existing government initiatives may assist such efforts, including programs that support industry-based research training and collaborative innovation.

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FIELD AND RESEARCH LEVEL TESTING OPPORTUNITIES

1. In-canopy sprinkler cooling can reduce organ temperature by more than 10 °C and has been used successfully in viticulture since the 1950s. However, site-specific optimisation is required with respect to phenological stage, prevailing weather conditions, and disease risk management. Water quality is an important consideration, although the volumes required are trivial compared with irrigation requirements.

2. Water deficit management practices offer opportunities for substantial economic savings and productivity gains. Regulated deficit irrigation requires minimal capital expenditure but demands careful management. Partial root-zone drying requires greater capital investment but is less management-intensive. Both approaches require optimisation for site and cultivar. Water savings, combined with improved production outcomes, are commonly reported to be in the order of 20–80% relative to standard practice.

3. Judicious application of ethephon may mimic some of the physiological effects of short photoperiods and improve reserve accumulation. It is also likely to interact positively with water deficit management practices.

4. Paclobutrazol applied immediately after pruning has been demonstrated as an effective means of preserving inflorescences and improving yield in hot production regions. However, site-specific evaluation is required, and the method of application requires optimisation. Application through the irrigation system appears to be the most effective and economical approach, although responses are influenced by soil type and potential carry-over effects that require assessment.

5. This review identifies several pathways for double-cropping systems that may increase annual yields to levels comparable with those achieved in traditional production regions. These approaches require evaluation from both economic and practical perspectives and may not be suitable for all northern production areas.

6. Inter-row cover cropping, selected according to seasonal conditions, could improve soil temperature regulation and enhance biological diversity. Such systems may also facilitate the adoption of integrated pest management (IPM) practices. However, cover crops should be managed as a production input and allocated an appropriate share of available water resources. Adoption of alternative vineyard structures, such as the Link trellis, may provide additional benefits.

7. Data collected as part of this program suggest that reserve cycling may be inefficient. Support for fundamental research into the signalling pathways involved could ultimately lead to significant gains in productivity and resource-use efficiency.

8. Existing models used to guide sprinkler cooling management are inadequate. The broader horticultural industry could benefit from the development of improved tools for managing heat stress. Current models are primarily focused on human thermal comfort and air temperature. Future models should instead focus on the evaporative cooling of intermittently wetted surfaces and the transfer of heat through plant tissues.

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Project Vision

To support the development of a profitable table grape industry in northern Australia through:

- diagnosing the physiological, climatic, and pest factors limiting profitability of table grape production;
- identifying means for ameliorating or resolving those limitations;
- identifying knowledge gaps and carrying out research to identify means to resolve one or more priority issues in the medium term; and
- conveying that knowledge to partners and industry.

Key points for industry

0.1 Introduction

This project was undertaken as a component of a Cooperative Research Centre for Northern Australia (CRC–NA) research project that sought to enable a more profitable table grape industry in Northern Australia. The project was a collaborative activity involving staff of the University of Western Australia and of the Department of Primary Industry and Regional Development (WA) (DPIRD) with financial and in–kind support from Fruitico Pty Ltd, a subsidiary of Fresh Produce Australia Pty Ltd (FPG) and from DPIRD.

This component involved three analyses. A survey and description of the climate of table grape growing regions in Australia and how they related to key reference sites internationally: notably the Levant (Mediterranean) and Brazil. The Levant was selected as representing the 'ideal' climate for table grape production and Brazil, as a region with a well established and successful, tropical table grape industry. Second, a review of the role of particular climatic factors as limiting productivity in northern Australia and, lastly, an analysis of agronomic practices to mitigate the impact of those climatic factors identified as limiting productivity.

0.2 Climate analysis

A climatic analysis of 21 Australian and 11 international sites identified six groups with similar climates and thus similar climate management issues. These groups do not match conventional geographic climate description systems such as those based on latitude (Temperate to Tropical) or Köeppen Geiger (a combination of thermal, aridity and seasonal descriptors). They are displayed in Figure 1. Coolup, Echuca and Applethorpe group with sites in the Levant (Lebanon, Jordan) and the Caucuses. The Levant sites are proposed as the natural habitat of the wild form of the table grape form of the grapevine. It is also where it was first cultivated. These are proposed as the ideal locations for producing table grapes.

Closely related to this group are the conventional inland table grape producing regions of the Murray Darling region. These differ from the former in being inland and exposed to a greater seasonal and daily range of temperature. The high temperature in summer is a notable feature of this group. Kununurra in Western Australia and TiTree in the Northern Territory form a group of their own with no international equivalent identified among the regions included in the study.

Roebuck, near Broome in Western Australia is located in a climate group that includes two successful Brazilian regions: Petrolina and Limoeiro du Norte. Thus the agronomic practices that have developed for those sites should be readily adapted to Roebuck. Emerald, St George and Carnarvon form an Australia-only group and could cooperatively develop site-specific agronomic practices. What these might include is considered later in the adaptive management section.

Mareeba is a unique site, climatically, in Australia but is well matched to successful sites in Brazil *e.g.* Londrina and Joao Pinheiro.

The climate analysis also considers tools for estimating the potential for field cooling vines and proposes a simple method to assess that potential based on readily available climate data: wet bulb depression (the difference between dry bulb and wet bulb temperature). This is used to identify the regions and periods that would be most suitable.

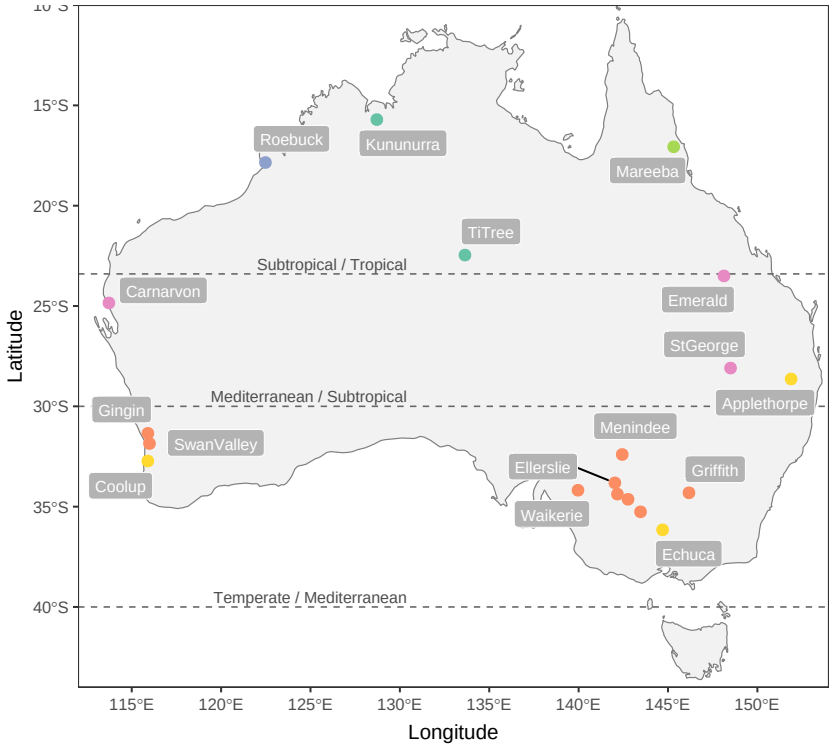


Figure 1: Map of Australia with the locations coloured by climate group as defined by this study. Locations with the same colour point have similar climates.

0.3 Grapevine productivity and climate

The climatic and regional variables that have the greatest impact on productivity are extreme daily maximum temperature, night time temperature (daily temperature range), rainfall and the yearly range of day length experienced.

All Australian sites bar Coolup, Echuca, and Applethorpe experience productivity damaging high temperatures during the growth cycle of the vine. While research has devoted most attention to the effect of heat waves and extreme high temperature on photosynthesis, this is probably not the most important aspect for productivity. More important is the effect of high temperature and sustained high daily temperature on respiration. Figure 2 shows a graphical summary of the role of high temperature enhanced respiration in limiting net productivity.

Grapevines, and indeed most plants can adapt to an air temperature at or a little above 37°C. The impact of high temperature on respiration however is such that much of the daily photosynthesis activity may be respired by all organs of a vine: leaf, cane, trunk and root. Respiration approximately doubles for every 10°C rise in temperature (Figure 2).

Temperature however affects all growth processes, particularly those related to the development of bunches. Temperature > 32°C reduce bunch initiation and further development of the bunch primordium during the prior season. This is a considered a key issue demanding management. Figure 3. illustrates the practical outcome in the vineyard.

Not only does extreme temperature limit the production of the bunch primordium, it also limits its further development during bud burst. Smaller bunches have weaker power to compete with the vegetative shoot for reserves. This leads to bunch shedding in extreme cases.

A low range of day length through the year leads to continuous growth and competition between vegetative growth and reserve accumulation. This is potentially a severe constraint to productivity in the succeeding cropping cycle. It also means the natural cycle of spring growth, autumn rest is disrupted. This cycle sets the physiology for recycling of root stored nutrients on which the next production cycle, at first, depends entirely on. The 'shut-down' practices adopted to emulate this need review. This is an absolutely critical aspect of productiv-

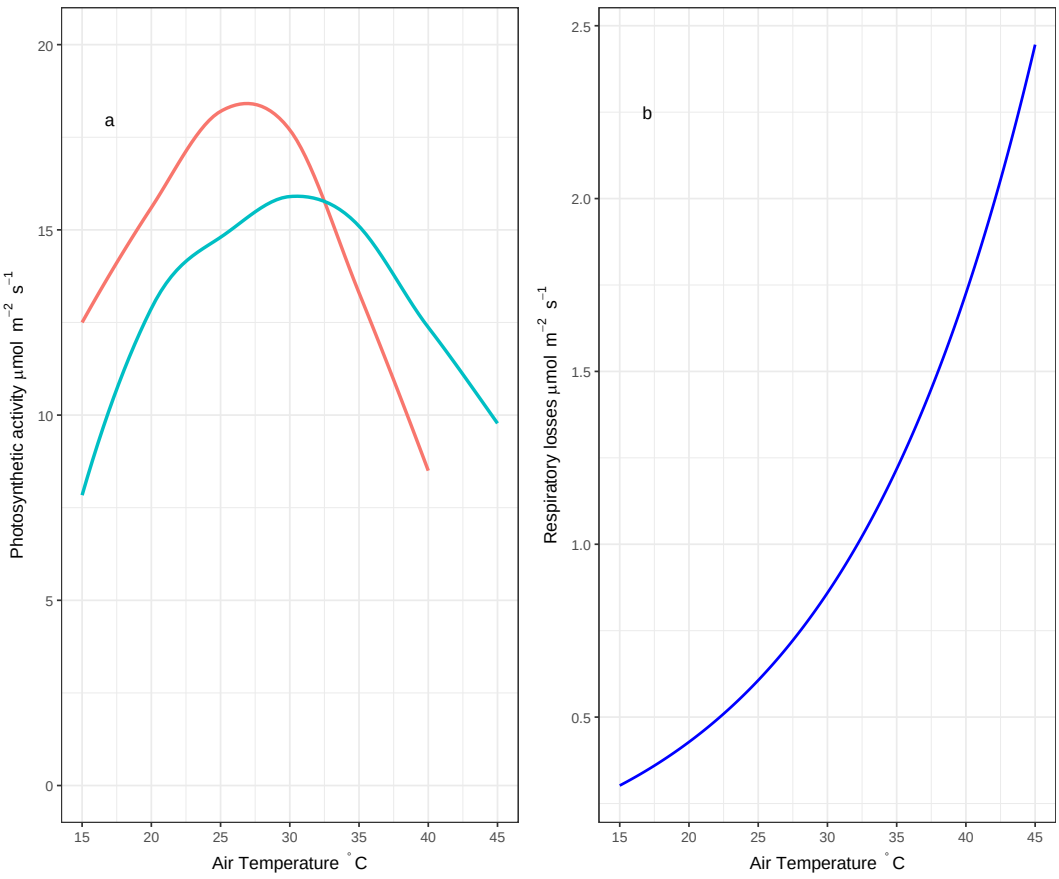


Figure 2: Graphs showing the response to two grapevine cultivars to temperature. (a) The response of photosynthetic activity and (b) the loss of the results of photosynthetic activity by respiration. Redrawn from (Greer, 2017, 2022).

ity which require leaf stored nutrients to be returned to the trunk and re-used in the next growth cycle, along with the root stored nutrients. Active sap bleeding at pruning is a strong indicator that the process is functioning to recycle root stored nutrients.

0.4 Adaptive management

This section reviews each of the key production cycle management practices available to the manager. Selection of varieties adapted to the local environment is the first and probably the most important step. Hybrid varieties may perform best but may not be suited to the Australian market but some *V. vinifera* cultivars show a similar capacity (Figure 3). If a cultivar is not well adapted then active management becomes critically important, especially for northern tropical and subtropical regions. Management in such regions differs in important ways from systems that are practiced in southern regions.

The first new management practice considered is cycle timing. Avoiding rainfall during the ripening phase and harvest is vital. This principal is then applied to assessing the potential for multiple harvest cycles per year. Only cultivars with a short production cycle will succeed. Sultana is used as an example but it is poorly adapted to high temperature during inflorescence formation and development phases. Two locations, Roebuck and Kununurra, are identified as potentially suited to multi-annual cropping. Others such as the Carnarvon group may be suited to alternative multi-cropping practices that split the production into two times using canes from a single pruning. This may put product into a late autumn/early winter market gap.

The greatest potential, by far, for increasing productivity is proposed to be field hydrocooling. The history of this technique in viticulture extends as far back as the 1950's. The technology is yet immature because attention has generally focussed on perceived cooling (air) rather than object cooling by surface evaporation. Despite this, reports of important benefits are well supported by research and practice in other industries (e.g. apple).

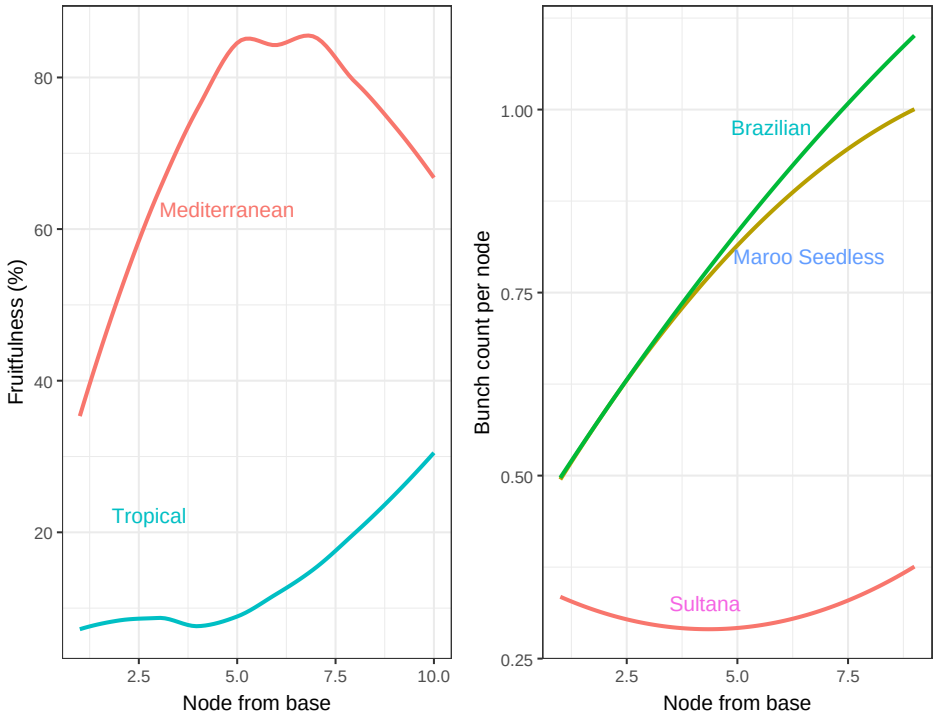


Figure 3: Average bud fertility for Sultana, Perlette and Superior Seedless for vines growing in either a tropical or a Mediterranean climate (left). Comparison of the fertility of Brazilian cultivars adapted to a tropical climate, Marroo Seedless, an Australian, CSIRO bred cultivar and Sultana. All growing under tropical conditions.

An option available immediately is the targeted use of plant growth retardants to protect the development of inflorescences during the formation phase and development post bud burst. There is a record of this being a useful strategy in other high temperature regions of table grape production.

This report strongly recommends consideration of the use of partial root zone drying as a tool to manage excessive vegetative growth and thus its competition for resources with the bunch and with reserves. This technique has been reported to provide gains in water use efficiency and yield that very from 20 to 80%.

Finally, attention to soil health and temperature should provide tangible benefits. The use of cover crops or mulch to shade the soil will reduce reflection of radiation and reduce soil temperature (and thus respiration).

0.5 Known Unknowns - the need for R&D

Many aspects of the biology of the grapevine are surprising poorly documented. Areas such as photosynthesis are well understood but there is very little published research on topics that would support not only table grape production in northern Australia but other intensive cropping, high value industries. They will also potentially benefit the southern industry.

The regulation of the carbon (photosynthate) cycle is not understood or fully described. Not for any woody perennial. This is quite surprising. It is generally considered to lie within 'dormancy' but evidence suggests that mechanisms related to stress tolerance (freezing) are at work. How these interact with those related to drought tolerance are relevant to the agronomic practice of 'shut-down' and recycle in low latitude regions of Australia and elsewhere.

Published irrigation management research focused on the table grape industry is almost non-existent. Yet this is a high value industry and water use efficiency is becoming critically important as the volume of water available for irrigation becomes more constrained and the demand increases. Such research is of strategic importance to industry.

High temperature is having an impact globally and the research done in the context of the historical temperature range is becoming redundant. It was considered that high temperature favours bunch initiation and growth. It is becoming clear that limits are now being exceeded and extreme temperature leads to lower productivity. A better understanding is required to inform management.

Vineyard floor management is an active area of research internationally for reasons of soil health and integrated pest management (IPM) as well as moderating soil temperature. There are opportunities throughout the table grape industry to re-examine and implement this practice. In the arid tropics, the crop will need to be managed as a companion crop, an important aspect of the overall management of a vineyard. In southern areas, winter rain fed crops can be left in place as a straw mulch should frost risk be manageable.

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Chapter 1

Opportunities for table grape production in northern Australia

Summary

Australia has a significant opportunity to expand table grape production into tropical and subtropical regions, particularly to supply markets during November and December when domestic availability is limited and imports are required. International examples, especially from northeastern Brazil, demonstrate that profitable production in low-latitude environments is achievable when production systems are adapted to local climatic conditions. However, substantial barriers remain. Yields in tropical and subtropical regions are generally lower and more variable than those obtained in traditional Mediterranean production areas. The absence of strong seasonal cues promotes excessive vegetative growth, while high temperatures and limitations in water supply further constrain productivity. Addressing these factors through improved crop management, irrigation strategies and a better understanding of grapevine physiology in tropical environments is essential if the economic potential of northern Australian table grape production is to be realised.

1.1 Background

Table grapes have been one of Australia's fastest-growing fresh fruit exports. There is significant potential to expand cultivation into subtropical and tropical regions as a high-value, labour-intensive perennial crop. However, Australia remains a relatively minor producer in the global context.

The non-climacteric nature of grape berries limits their storage life and constrains their marketing as a premium fresh product. Unlike bananas, apples and tomatoes, grapes do not continue to ripen after harvest. Consequently, imports are required to meet domestic demand outside the main Australian production season of January to March or April. Production in subtropical regions, or under protected cropping systems, creates opportunities for earlier harvests during November and December, thereby reducing reliance on imports while capturing substantial price premiums. Table 1.1 illustrates the narrow market window currently available for grapes produced in subtropical regions.

Resolving the production constraints observed in both tropical and subtropical regions could enable sustained and profitable production of a crop that offers relatively low environmental impact while generating significant economic activity and regional employment. Because grapes cannot ripen after harvest and have limited storage potential, extending market opportunities ultimately requires extending the production season. Australia's broad geographic range makes it particularly well suited to such an approach (*c.f.* Chile).

The feasibility of grape production in tropical regions has been recognised for centuries. Alexander von Humboldt documented grape cultivation in Venezuela during his explorations of the 1790s. More recently, large-scale production systems have been developed in regions such as the semi-arid tropics of northeastern Brazil. Nevertheless, production challenges remain, even where considerable government investment and research support have been provided. A recent report funded by the CRC for Developing Northern Australia documents grower

perceptions of opportunities and threats associated with northern Australian production (Sangha et al., 2022).

Table 1.1 shows that Victoria dominates Australian production and that the greatest opportunity for import replacement occurs during November, a period that could potentially be supplied by growers in tropical and subtropical regions. The table also highlights seasonal gaps in supply, some of which are currently filled by imports. While the Australian table grape industry is strongly export-oriented, with exports valued at approximately $623 million in 2020, import replacement ($83 million in 2020) and expansion of regional production are likely to be the primary economic drivers for development in northern Australia. Grapevines evolved and were domesticated in the highly seasonal environments of eastern Europe, western Asia and North Africa (Dong et al., 2023). Consequently, the grapevine production cycle is genetically adapted to Mediterranean and Mediterranean-like climates. In these environments, production typically requires relatively few inputs beyond the management of pests and diseases. In low-latitude climates, however, the seasonal cues that regulate dormancy, shoot growth and reproductive development are weak or absent. The result is often excessive vegetative growth at the expense of fruit production. High temperatures also constrain yield and fruit quality and must be actively managed.

1.2 Production and Destination

Figure 1.1 shows recent trends in Australian table grape production, exports, imports and domestic consumption. Between 2015 and 2025, production increased steadily at an average rate of approximately 14.6 thousand tonnes per annum, while exports increased by approximately 8 thousand tonnes per annum. Domestic consumption remained relatively stable over the same period, whereas imports declined by around 2.9 thousand tonnes per annum.

The declining trend in imports suggests that the opportunity for import replacement may be diminishing. This may reflect changes in consumer purchasing behaviour during winter or the increasing ability of domestic producers to satisfy off-season demand.

Table 1.1: Seasonal availability by state and month for the 2024 financial year. Note the availability chart is based on data for the year 2025 except for the imports, 2021. Source: HortInnovation Australia Pty Ltd

Availability legend	High	Medium	Low	None

State	Tonnes	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Victoria	130,642												
New South Wales	29,861												
Queensland	14,931												
Western Australia	9,332												
South Australia	933												
Northern Territory	933												
Imported	5,817												

1.2.1 Yield Gap

Yield gaps are substantial in Australian tropical and subtropical production regions. In addition to generally lower productivity, year-to-year variation is often high, particularly in subtropical environments where yields may fluctuate by approximately $\pm 50\%$ around the mean (Table 1.2; Fig. 1.2).

In extreme cases, yield differences between regions may exceed 30-fold, although more commonly they are likely to be two- to three-fold. Even modest improvements in yield can substantially influence profitability and increase grower confidence in future investment decisions. A latitudinal difference of only 8° is associated with a major reduction in yield per vine (Table 1.2). This constraint to profitability requires targeted research and development.

1.2.2 Water Supply

Globally, table grape production is concentrated in regions with dry summers because low rainfall during fruit ripening minimises disease pressure and fruit damage (Considine, 1973). Consequently, irrigation is required to compensate for deficits in natural water supply (the grapevine evolved in river valleys).

In Western Australia, expansion of production in regions such as Carnarvon and Broome depends on finite groundwater resources, which represent a major constraint to further development (Anon, 2014). Increasing

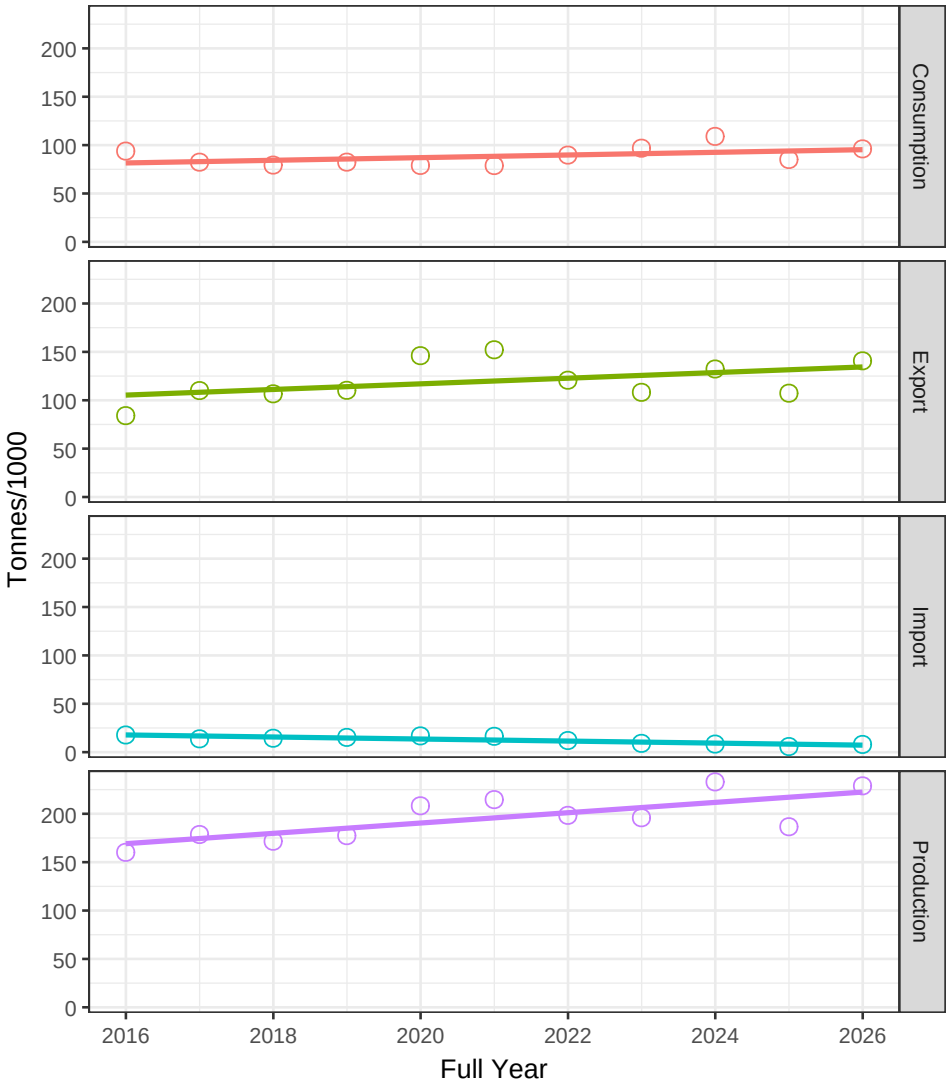


Figure 1.1: Australian production, destination and imports of table grapes for the full years 2015 to 2025. Consumption hs been estimated as Production less Export, plus Imports. Source: HortInnovation Australia Pty Ltd

.

the yield of existing plantings is therefore one of the most effective means of improving water-use efficiency. Additional opportunities may exist through the adoption of deficit irrigation strategies, particularly partial root-zone drying, which has demonstrated benefits in grape production systems (Dry et al., 2001).

Table 1.2: Estimates of yield of table grapes by latitude

Location	Yield kg/vine	Latitude
Myalup WA (c.f. Sunraysia)	45 to 55 (60)	32.9
Swan Valley WA	15 to 25	31.8
Carnarvon WA	7.5 (as low as 2 to 3)	24.9
Central Highlands Qld	2.1 to 18.1, mean 8	23.9

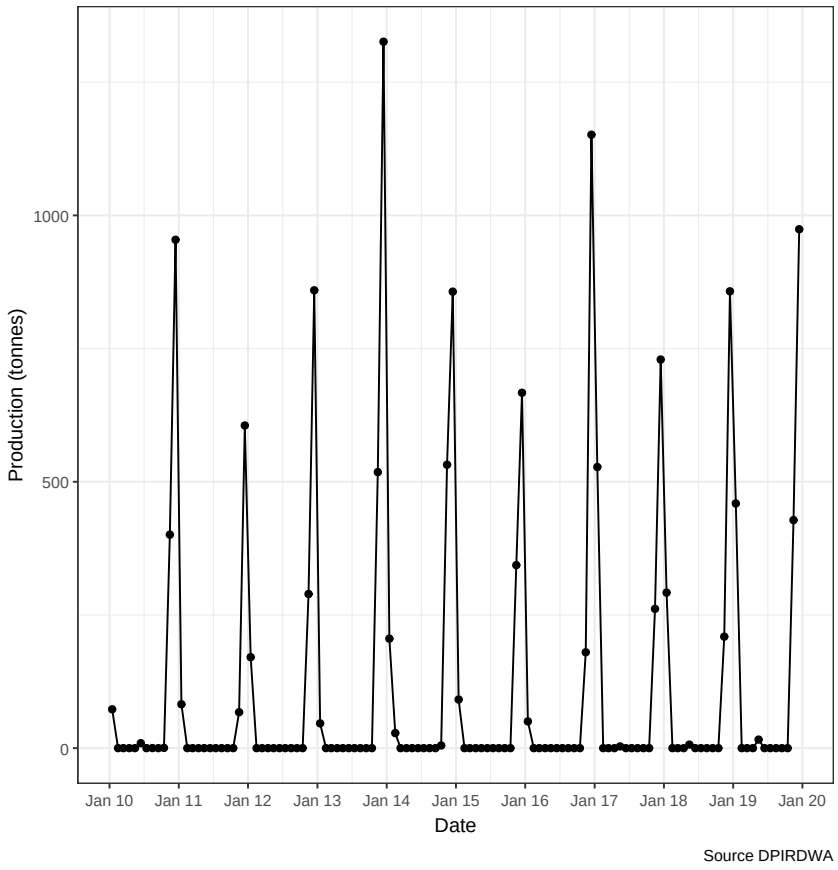


Figure 1.2: Seasonal records of table grape production in the Carnarvon region for the years 2010 to 2020. Source: Department of Primary Industry and Regional Development, WA.

1.3 Key References Concerning Production and Production Practices in Brazil

Phenological behavior of six seedless grape varieties in the tropical conditions of Vale do Rio São Francisco, northeastern Brazil	Leão et al. (2000)
Grape management techniques in tropical climates	Camargo (2005)
Double cropping of table grapes in Brazil.	Pommer (2006)
Grape growing and processing in Brazil.	Camargo et al. (2008)
Disciplining capital: export grape production, the state and class dynamics in north-east Brazil.	Selwyn (2009)
Globalization of fresh fruit products: The role of public agencies and the transformation of the Petrolina-Juazeiro valley.	Valente (2009)
The impact of breeding on fruit production in warm climates of Brazil	Pommer and Barbosa (2010)
Towards the developing of well adapted grapes for tropical regions.	Ritschel et al. (2010)
Globalized horticulture: The formation and global integration of export grape production in northeast Brazil.	Selwyn (2010)
Tropical viticulture: specificities and challenges for a quality viticulture	Carbonneau (2011)
Globalization, food quality and labor: The case of grape production in north-eastern Brazil	Bonanno and Salete Barbosa Cavalcanti (2012)
Grapevine performance and production strategies in tropical climates.	Camargo et al. (2012)
Phenological behaviour and thermal requirements of seedless grapes grown in the Submiddle São Francisco River.	dos Santos et al. (2013)
Phenological and thermal demand of table grape cultivars grown in tropical zones of Brazil.	Leão et al. (2013)
Challenges and opportunities to growing table grapes in sub-tropical/tropical regions.	Leão (2014)
Up scaling table grape water requirements in the low-middle São Francisco river basin, Brazil	de C. Teixeira et al. (2014)
Socio–economic aspects of irrigation agriculture as livelihood for rural families in Brazil's semi–arid northeast.	Hagel et al. (2019)
Genetic resources for table–grape breeding in Brazilian tropical semi-arid regions.	Leão (2019)

Chapter 2

Geography, Ecology and Climate

2.0.1 Summary

Australian table grape production regions were benchmarked against selected national and international locations to identify and quantify the climatic factors most likely to influence growth, productivity and adaptation. Six broad climatic classes were identified, allowing Australian production regions to be matched with climatically similar locations, internationally. This framework provides a basis for transferring knowledge and production practices from comparable environments elsewhere in the world.

2.0.2 Geography

Grapevines evolved within particular ecosystems rather than within a set of climatic statistics. Therefore, ecological classifications may provide insight into adaptation and productivity that is not captured by climate variables alone.

Australian table grape production spans a remarkable geographic range, extending from Mareeba (17.1°S) to Echuca (36.2°S) (Figure 2.1). These locations encompass both traditional production regions, such as those of the Murray Valley, and regions that lie well beyond the climatic environment in which the cultivated grapevine evolved and was domesticated (Dong et al., 2023; Levadoux, 1956; Vavilov, 1950).

Variation in photoperiod is perhaps the most obvious environmental change encountered with latitude (Figure 3.2). However, photoperiod is only one component of a broader climatic complex influencing plant growth, phenology and productivity. In tropical regions, plants often rely on rainfall seasonality and endogenous biological rhythms to synchronise growth and reproduction. In contrast, plants of temperate and sub-equatorial regions are more strongly regulated by annual changes in daylength and temperature.

Plant distribution and vegetation structure are generally more closely associated with environmental conditions than with latitude alone. Consequently, climatic classification systems such as that of Köppen and Geiger were developed to provide a more biologically meaningful framework for describing landscapes (Geiger, 1961). These classifications often transcend the conventional human perception of climate based solely on latitude. For example, Figure 2.2 highlights the dominant influence of proximity to the ocean on regional climates throughout Australia.

Many additional factors contribute to landscape character, including elevation, topography, soils and geology. While these factors are important determinants of agricultural performance, they were not considered explicitly in the present analysis, which focuses on climatic factors influencing grapevine productivity.

Vegetation and water availability have historically been among the most important considerations guiding agricultural settlement and land use. Figures 2.3 and 2.4 provide two complementary perspectives on Australia's production environments. The first illustrates vegetation patterns and therefore the natural capacity of landscapes to support plant growth. The second incorporates a broader suite of ecological attributes through bioregional classification. Together, these frameworks provide valuable context for understanding the environmental

challenges faced by growers and agronomists in different regions.

It is noteworthy that many table grape production regions are located near population centres and coastal corridors, while others have developed primarily in response to economic opportunities such as the availability of irrigation water, relatively low land values or government-supported agricultural expansion. The resulting diversity of production environments highlights the need for a physiologically based framework for comparing regions and identifying the climatic factors most likely to constrain productivity.

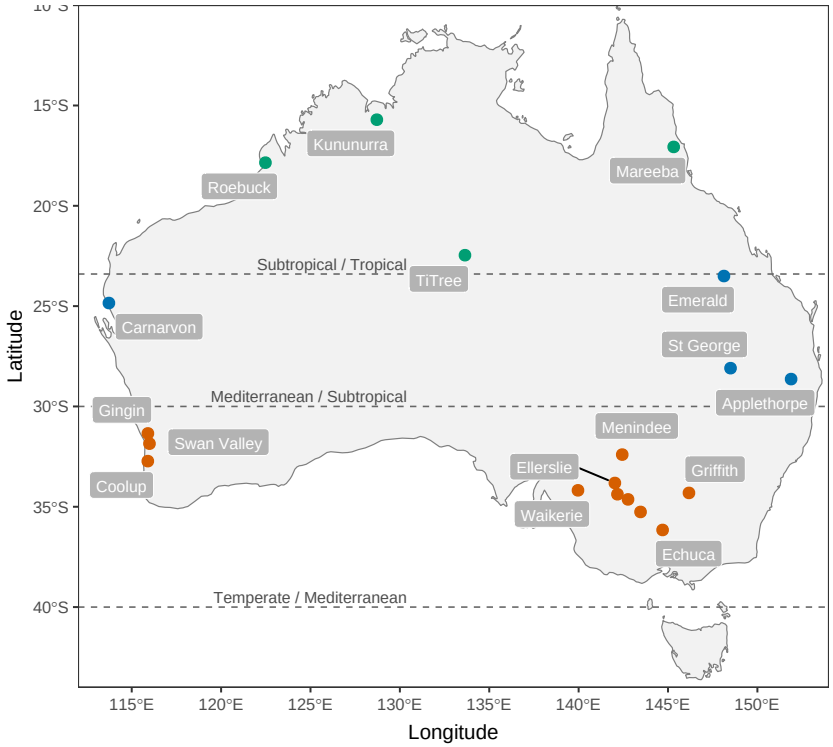


Figure 2.1: Map of Australia showing the locations included in this study and the latitudinal lines delineating the general geographical climatic descriptors. Climate groups: ● Tropical, ● Subtropical, ● Mediterranean, and ● Temperate.

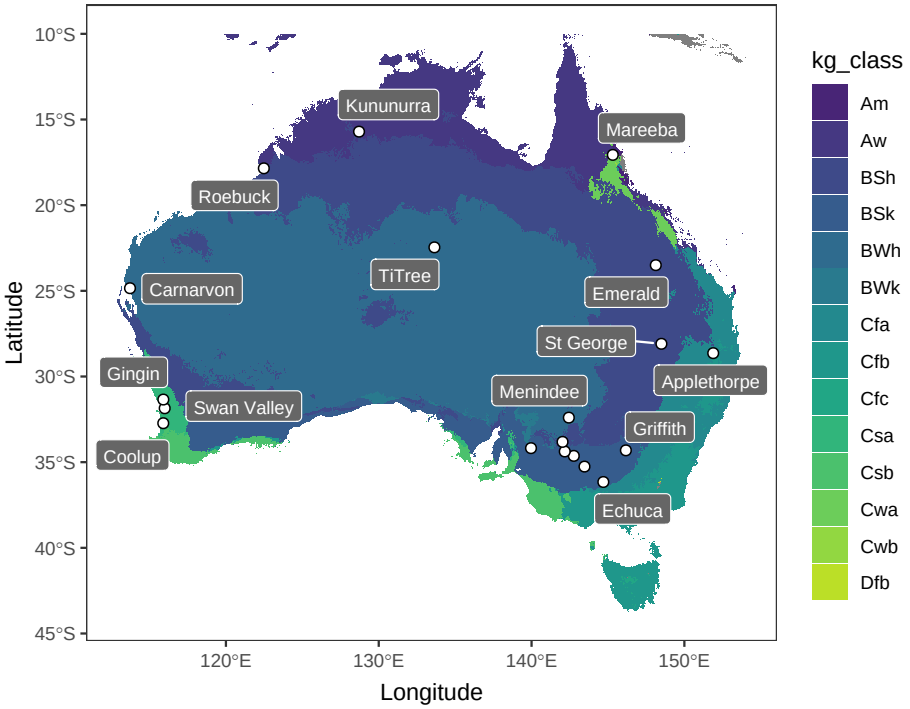


Figure 2.2: Location of the Australian sites in accordance to Köeppen Geiger climate classification.

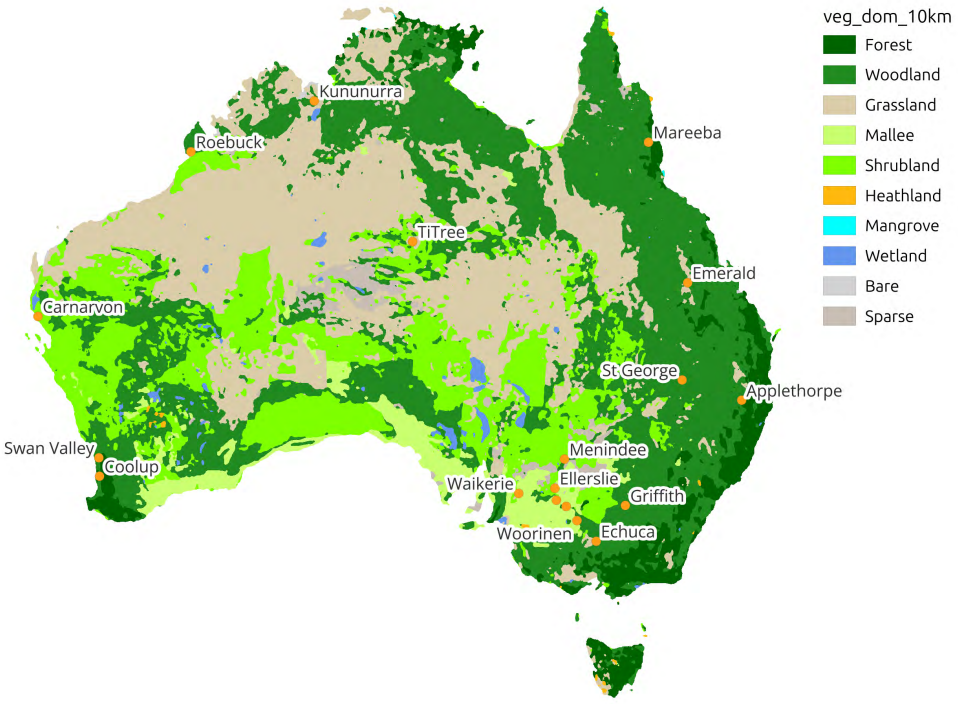


Figure 2.3: Map of the major vegetation associations based on pre-European settlement values with those containing study sites highlighted. This an abridged (merged) list for clarity at this scale.

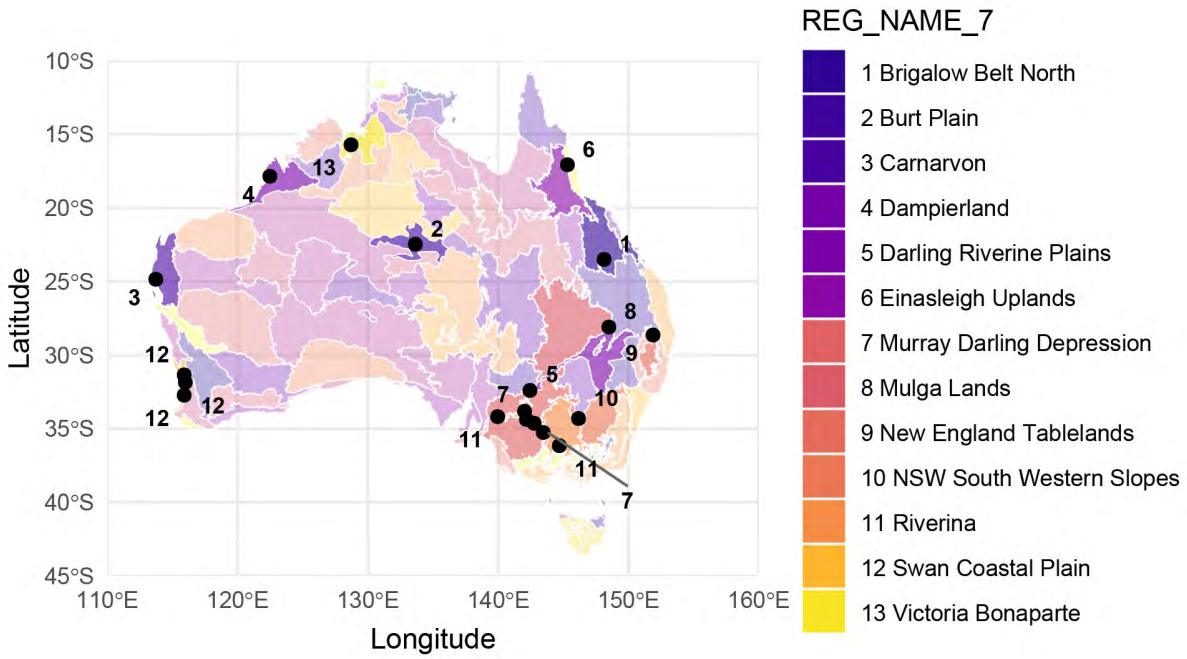


Figure 2.4: Map of the major biological regions of Australia (IBRA–7) with those containing study sites highlighted.

Table 2.1: Summary table of Biogeographic regions of interest (Thackway and Cresswell, 1995)

Site	Bioregion	Abbreviated description
Applethorpe	New England Tablelands	Comprise an elevated plateau on Paleozoic sediments, granites and basalts dominated by tall stringbark, box and peppermint eucalypts (*E. calignosa, E. nova-anglica, E. melliodora, E. blakleyi*).
Carnarvon	Carnarvon	Quaternary marine, alluvial and aeolian sediments overlying Cretaceous strata. Production confined to alluvial flats with samphire and saltbush low woodlands. Arid.
Coolup	Swan Coastal Plain	Low plain with paperbark in swampy areas, Banksia spp on sands.
Echuca, Waikerie, Woorinen	Riverina	An ancient river flood plain comprising unconsolidated sediments. Eucalypt woodlands, atriplex shrublands divided by extensive grasslands and swamps.
Ellerslie, Menindee	Darling Riverine Plains.	Clay alluvial fans and plains experiencing winter and summer rainfall. Vegetation principally eucalypt woodlands.
Emerald	Brigalow belt north	Bowen basin comprising principally open woodland. The geology of the region is very complex containing regions derived from Pre–Devonian to Permian to Tertiary. Vegetation dominated by acacia woodlands (*Acacia harpophylla*).
Gingin	Swan Coastal Plain	The region of interest is at the base of the scarp with coarse lateritic sands and alluvial silts with a jarrah (*E. marginata*) woodlands.
Griffith	NSW Western Slopes	described as an extensive series of foothills with a vegetation consisting of wet sclerophyll woodlands of peppermints, box and ironbark (*E. radiata, E. melliodora, E. creba*).
Kununurra	Victoria Bonaparte	Quaternary marine sediments forming red earth and black soil plains supporting samphire (*Sporobolus*) spp and an open savanna of tall grasses.
Mareeba	Einasleigh Uplands	Paleozoic granitic and basaltic sediments forming a high plateau. Vegetation dominated by ironbark, eucalypt woodlands.
St George	Mulga Lands	Cainozoic sediments forming plains and low hills with red earth and lithosol soils. Vegetation predominantly mulga (*Acacia aneura*).
Robinvale, Sunraysia	Murray Darling Depression	Sand or clay plains dating from the Tertiary and Quaternary eras, often overlain by aeolian sand dunes. Mixed woodlands ranging from mallee (*Eucalypt* spp), *Allocasuarina* and acacia to heathlands.
TiTree	Burt Plain	Pre-Cambrian granitic plains and ranges with acacia woodlands (including *A. aneura*) on red earth soils.
Roebuck Plains	Dampierland	Varies from quaternary sandplain overlying Jurassic and Mesozoic sandstones. The Roebuck Plains consist of Pindan covered with low forests of *Melaleuca acacioides*

2.1 Regional and Local Site Climate

2.1.1 Approach

This analysis is based on climate data extracted from the SILO and ERA5 databases using the point-location protocol described in Chapter 6. A representative vineyard location was selected for each region (Table 2.2). While these locations characterise the broader production districts, variation within regions may occur due to differences in topography, proximity to the coast, elevation and local landscape features.

To facilitate comparison between Northern and Southern Hemisphere locations, all dates were normalised relative to the summer solstice. Thus, in the Southern Hemisphere the annual cycle begins on 22 December, whereas in the Northern Hemisphere it begins on 22 June. Solar events are shown throughout to indicate season and enable dates to be inferred.

2.1.2 Climate and Climate Classification

The objective of this study is to place Australian table grape production regions within the context of both the probable climatic environment of grapevine domestication and a range of benchmark tropical and subtropical production regions. Temperature and aridity are primary determinants of plant productivity and, at their extremes, define the limits of successful cultivation. A suite of climatic variables was therefore assembled together with a number of derived indicators relevant to grapevine physiology.

The primary variables considered were:

- Daily maximum temperature (T_{max}, °C)
- Daily minimum temperature (T_{min}, °C)
- Relative humidity (%) at T_{max} and T_{min}
- Daily rainfall (mm)
- Total solar radiation (MJ m^{-2})
- Reference evapotranspiration (ETO, mm, short crop)
- Mean daily air pressure at ground level (kPa; ERA5 for all locations)

The locations were grouped according to climatic similarity to facilitate identification of climatically analogous regions and comparison with international production systems. Group membership was determined using Principal Component Analysis (PCA), with details provided in Chapter 6. In essence, PCA reduces the dimensionality of the dataset by identifying the major climatic gradients that account for differences among locations.

Figure 2.10 presents the basis of the ordination and the arrangement of locations within two-dimensional climatic space. The first principal component (PC1) explains most of the variation among sites and reflects a gradient associated with latitude, photoperiod range, night temperature and evaporative demand. Some of these variables are strongly correlated, positively or negatively (Figure 5.1). The second principal component (PC2) is associated primarily with moisture availability and atmospheric evaporative demand.

Figure 2.6 shows the distribution of sites within this climatic space together with the statistical grouping procedure. The yellow group comprises the traditional Mediterranean-type climates associated with the historical distribution of grapevine cultivation. The red group, the inland, Mediterranean-like group. The light green group contains the humid Brazilian tropical locations together with Mareeba. The purple group includes the remaining tropical and subtropical sites, including northern Australian production regions, Petrolina and the arid tropical location of Limoeiro do Norte.

The Mediterranean, maritime cluster includes sites from both the Levant and the Caucasus, together with Australian locations such as Echuca, Applethorpe and Coolup. Somewhat unexpectedly, Swan Valley and Gingin align more closely with the inland Murray-Darling production regions than with Mediterranean coastal environments. Figure 2.7 presents a simplified climate-space representation. In this analysis the horizontal axis is dominated by mean annual temperature, while the vertical axis reflects annual temperature range, a composite measure influenced by latitude, seasonality and continentality. This emphasises the dominant role of temperature in defining climatic similarity among locations.

The analyses that follow are based on the six climatic subgroups identified by the clustering procedure. These

broad climatic descriptors provide a useful summary of the environmental constraints that ultimately shape grapevine productivity and inform agronomic management. Table 2.2 summarises the geographic location, Köppen–Geiger climate classification and cluster membership of each site. Table 2.3 summarises the principal climatic characteristics of each group. Mean annual maximum temperatures range from approximately 21 °C to 33 °C, while corresponding minimum temperatures range from 10 °C to 22 °C. Reference evapotranspiration varies from approximately 1,200 to 2,100 mm year^{-1} and mean vapour pressure deficit ranges from 1.4 to 3.1 kPa, spanning environments from relatively equable to strongly water-demanding. These broad climatic descriptors provide a useful summary of the environmental constraints that ultimately shape grapevine productivity and inform agronomic management.

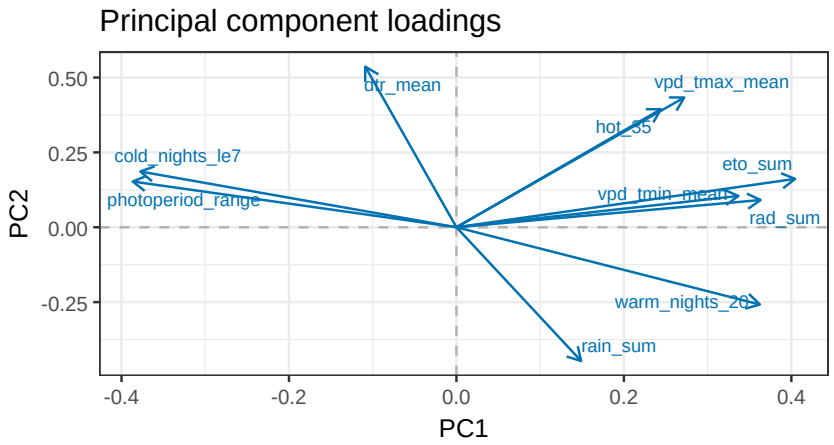


Figure 2.5: Biplot of loadings that apply to each of the following principal component plots. The arrows show the main direction of influence of each climatic attribute used to locate each site horizontally and vertically. Site located close to one another have similar climates, distant sites, different climatic influences.

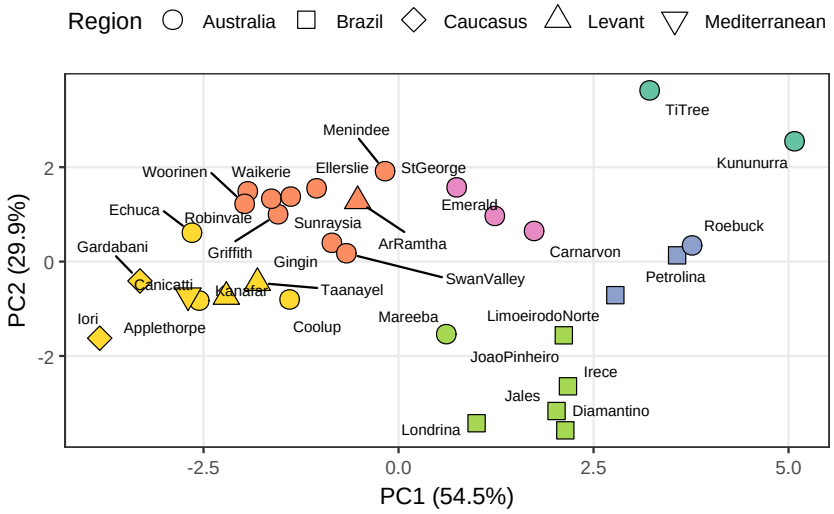


Figure 2.6: Cluster analysis of climatic similarity using the k-means method of analysis. The colours represent the 6 climate groups identified using the gap statistic.
Climate space colours:
1 ●, 2 ●, 3 ●, 4 ●, 5 ●, 6 ●

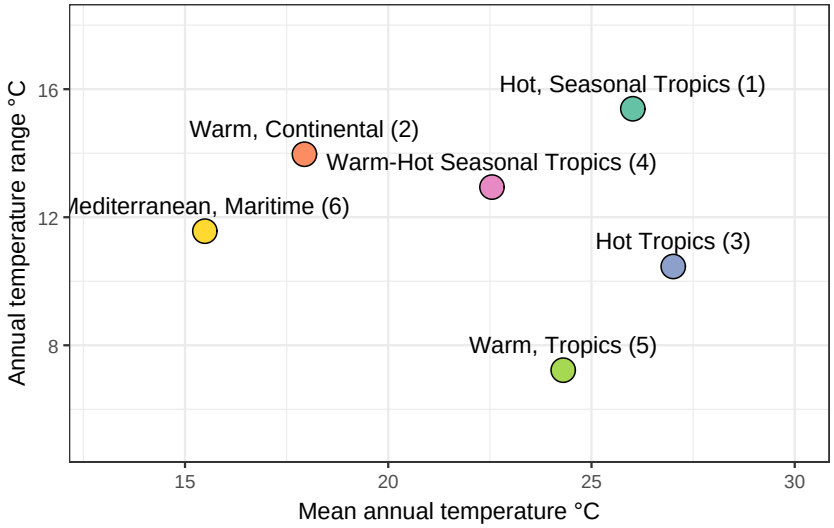


Figure 2.7: Plot of the six climate groups identified in Figure 2.6 on the basis of mean annual temperature as a heat index and annual temperature range as latitudinal/continentality index. Colours as per Figure 2.6.

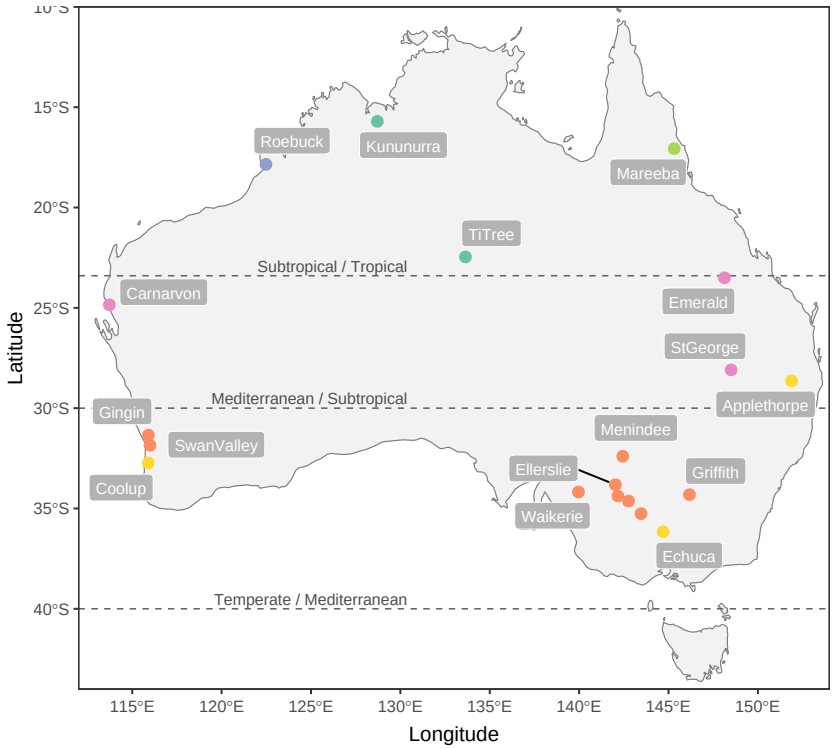


Figure 2.8: Map of Australia with each location coloured as per the groups identified in Figure 2.7

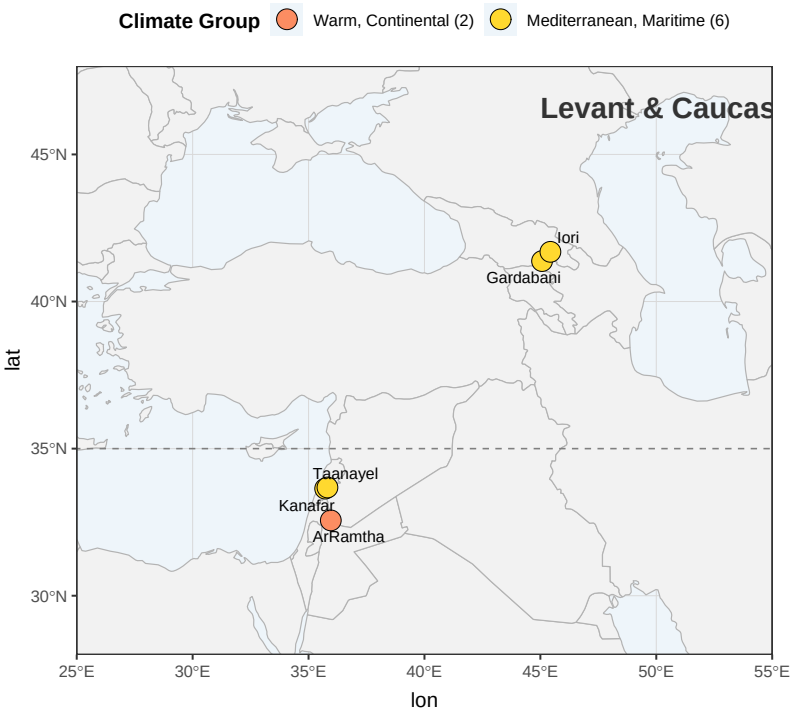


Figure 2.9: Map of the eastern Mediterranean region including the Levant and Georgia with each location coloured as per the groups identified in Figure 2.7. Note the Sicilian site is not shown.

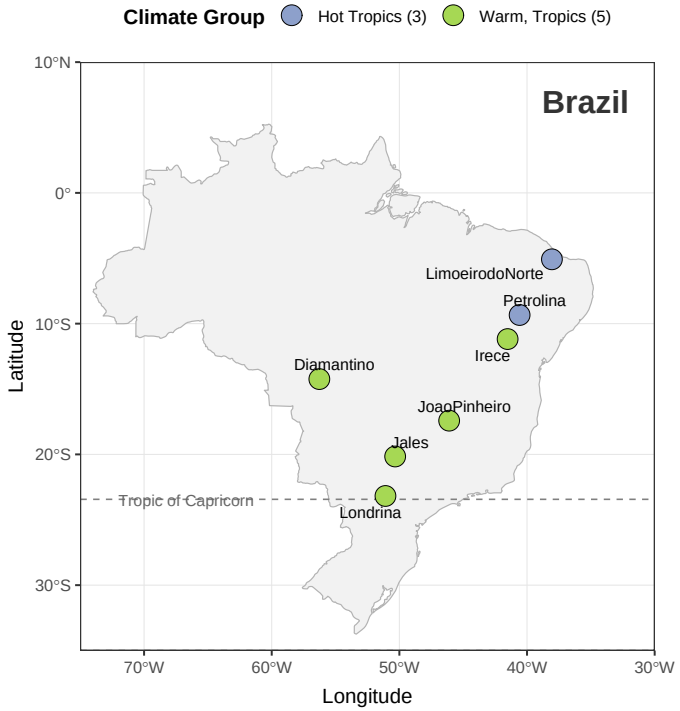


Figure 2.10: Map of Brazil with each location coloured as per the groups identified in Figure 2.7

Table 2.2: Site characteristics and cluster assignments.

Site_id	lat	lon	elev	kg_class	cl3	cl6
Hot, Seasonal Tropics						
Kununurra	-15.71	128.71	106	Aw	1	1
TiTree	-22.46	133.64	573	BWh	1	1
Hot Tropics						
Roebuck	-17.85	122.48	52	BSh	1	3

Table 2.2: Site characteristics and cluster assignments. *(continued)*

Site	Latitude	Longitude	Elevation	KG class	cl3	cl6
Petrolina	-9.34	-40.58	382	BSh	1	3
Limoeiro do Norte	-5.08	-38.05	70	Aw	1	3
Warm-Hot, Seasonal Tropics						
Emerald	-23.50	148.13	184	BSh	1	4
St George	-28.09	148.50	200	BSh	1	4
Carnarvon	-24.85	113.72	14	BWh	1	4
Warm Tropics						
Mareeba	-17.06	145.32	507	Aw	2	5
Londrina	-23.18	-51.09	566	Cfa	2	5
Joao Pinheiro	-17.42	-46.10	760	Aw	2	5
Irece	-11.18	-41.52	747	BSh	2	5
Jales	-20.16	-50.33	483	Aw	2	5
Diamantino	-14.24	-56.27	286	Aw	2	5
Warm Continental						
Griffith	-34.31	146.17	129	BSk	3	2
Woorinen	-35.26	143.46	62	BSk	3	2
Swan Valley	-31.85	115.99	13	Csa	3	2
Robinvale	-34.63	142.76	73	BSk	3	2
Gingin	-31.44	115.98	114	Csa	3	2
Waikerie	-34.18	139.96	46	BSk	3	2
Sunraysia	-34.38	142.17	57	BSk	3	2
Menindee	-32.34	142.43	62	BWh	3	2
Ellerslie	-33.82	142.03	41	BSh	3	2
Ar Ramtha	32.56	35.96	509	BSh	3	2
Mediterranean, Maritime						
Applethorpe	-28.64	151.89	821	Cfb	3	6
Coolup	-32.73	115.90	23	Csa	3	6
Echuca	-36.16	144.70	98	BSk	3	6
Gardabani	41.37	45.07	272	Cfa	3	6
Iori	41.69	45.43	200	Cfa	3	6
Kanafar	33.64	35.72	1020	Csa	3	6
Taanayel	33.68	35.81	850	Csa	3	6
Canicatti	37.38	13.84	546	Csa	3	6

2.2 The Average Climate by Climate Grouping

2.2.1 Hot Tropics

Figure 2.11 shows the average annual temperature regime for each climate group, ordered according to increasing seasonality. Roebuck Plains belongs to the Hot Tropics group and is the Australian location most similar climatically to the highly successful Brazilian production regions of Petrolina and Limoeiro do Norte.

These locations are characterised by a pronounced dry season centred on the winter solstice and a wet summer season that peaks near the autumn equinox. Solar radiation remains high throughout the year and generally follows changes in photoperiod. Evaporative demand and vapour pressure deficit are consistently high, reaching maxima during spring despite the relatively high humidity of these regions. Elevated humidity may limit the effectiveness of evaporative cooling and thereby increase the risk of heat stress during critical periods of growth and fruit development.

Table 2.3: Climatic summary of table grape vineyard sites grouped by climate regime. Values represent annual means or sums of site–year observations derived from SILO and ERA5 daily data.

Group	Sites (n)	Years (n)	Tmax (°C)	Tmin (°C)	Rainfall (mm)	Radiation
Hot Tropics (3)	3	26	31.9	21.7	637	7634
Warm, Tropics (5)	6	26	28.2	21.0	1047	7,352
Hot, Seasonal Tropics (1)	2	26	33.0	17.8	643	8,093
Warm-Hot Seasonal Tropics (4)	3	26	28.9	15.8	399	7,670
Warm, Continental (2)	10	26	25.2	11.0	355	6,855
Mediterranean, Maritime (6)	8	26	21.2	9.7	624	6,449

Group	ETo (mm)	RH Tmax	RH Tmin	VPD Tmax	VPD Tmin
Hot Tropics (3)	1,984	41.5	81.8	2.4	0.5
Warm, Tropics (5)	1,645	56.2	85.3	1.4	0.4
Hot, Seasonal Tropics (1)	2,105	29.7	68.3	3.1	0.7
Warm-Hot Seasonal Tropics (4)	1,769	38.8	80.9	2.2	0.4
Warm, Continental (2	1,508	38.3	84.5	2.1	0.3
Mediterranean, Maritime (6)	1,240	46.7	86.7	1.4	0.2

2.2.2 Warm Tropics

The Warm Tropics are characterised by lower and more equable annual temperatures than the Hot Tropics. Rainfall is concentrated in summer and autumn but extends throughout the year, resulting in the absence of a well-defined dry season.

In Brazilian production systems this climatic environment favours disease-tolerant hybrid cultivars because disease pressure remains high for much of the year. While such cultivars occupy important market niches in Asia, they are unlikely to gain widespread acceptance in traditional Australian fresh-fruit markets. Despite the high rainfall and humidity, annual evapotranspiration remains high. Vapour pressure deficit is comparatively stable throughout the year and displays less seasonal variation than any other climate group.

2.2.3 Hot, Seasonal Tropics

The Hot Seasonal Tropics are characterised by a prolonged dry season and consistently warm temperatures throughout the year. Kununurra and TiTree are representative Australian locations within this group.

Winter temperatures decline sufficiently to slow growth but generally remain within the range over which grapevine physiological activity responds approximately linearly to temperature (10 °C to 20 °C). The combination of warm temperatures and an extended dry season suggests that production systems based on two crops per year may be feasible. Vapour pressure deficit remains high throughout much of the year, imposing significant atmospheric demand on the vine.

2.2.4 Warm to Hot Seasonal Tropics

The established subtropical production regions of Emerald, St George and Carnarvon form part of this climate group. These locations experience very hot summer conditions, yet winter minimum temperatures often fall below the threshold for active growth (10 °C) without being sufficiently cold to induce complete winter acclimatisation or leaf fall.

The result is an extended growing season relative to traditional temperate production areas, suggesting the potential for two crops per year or three crops over a two-year cycle. Rainfall is concentrated in the summer months but remains relatively low throughout the year, making this group one of the driest identified in the analysis. Consequently, disease pressure is generally lower than in humid tropical climates, while irrigation becomes essential for reliable production.

2.2.5 Warm Continental

Warm Continental regions form the backbone of the Australian table grape industry. They are strongly seasonal and highly suited to conventional viticultural practices developed in Mediterranean environments.

Their predominantly inland location results in the largest day-to-night temperature range of any climate group. Summer temperatures are frequently extreme and likely impose limitations on photosynthetic performance and productivity. In contrast, spring conditions are close to optimal for flower initiation and inflorescence development. These regions experience the fewest rainfall events during harvest, reducing fruit quality risks, but also the highest vapour pressure deficits during fruit development and ripening, increasing evaporative demand and irrigation requirements.

2.2.6 Mediterranean Maritime

The Mediterranean Maritime group most closely resembles the climatic environment in which cultivated grapevines evolved and were first domesticated. The climate is strongly seasonal but is moderated by proximity to the ocean, resulting in a narrower annual temperature range and moderate levels of evapotranspiration and vapour pressure deficit.

Rainfall risk is greater than in the inland production regions and represents one of the principal constraints to production reliability. The combination of higher rainfall and elevated humidity also increases disease pressure relative to the continental environments. Coolup, Echuca and Applethorpe are representative members of this climate group. Overall, this climate class most closely approximates the environmental conditions to which traditional viticultural practices and modern *Vitis vinifera* cultivars are adapted.

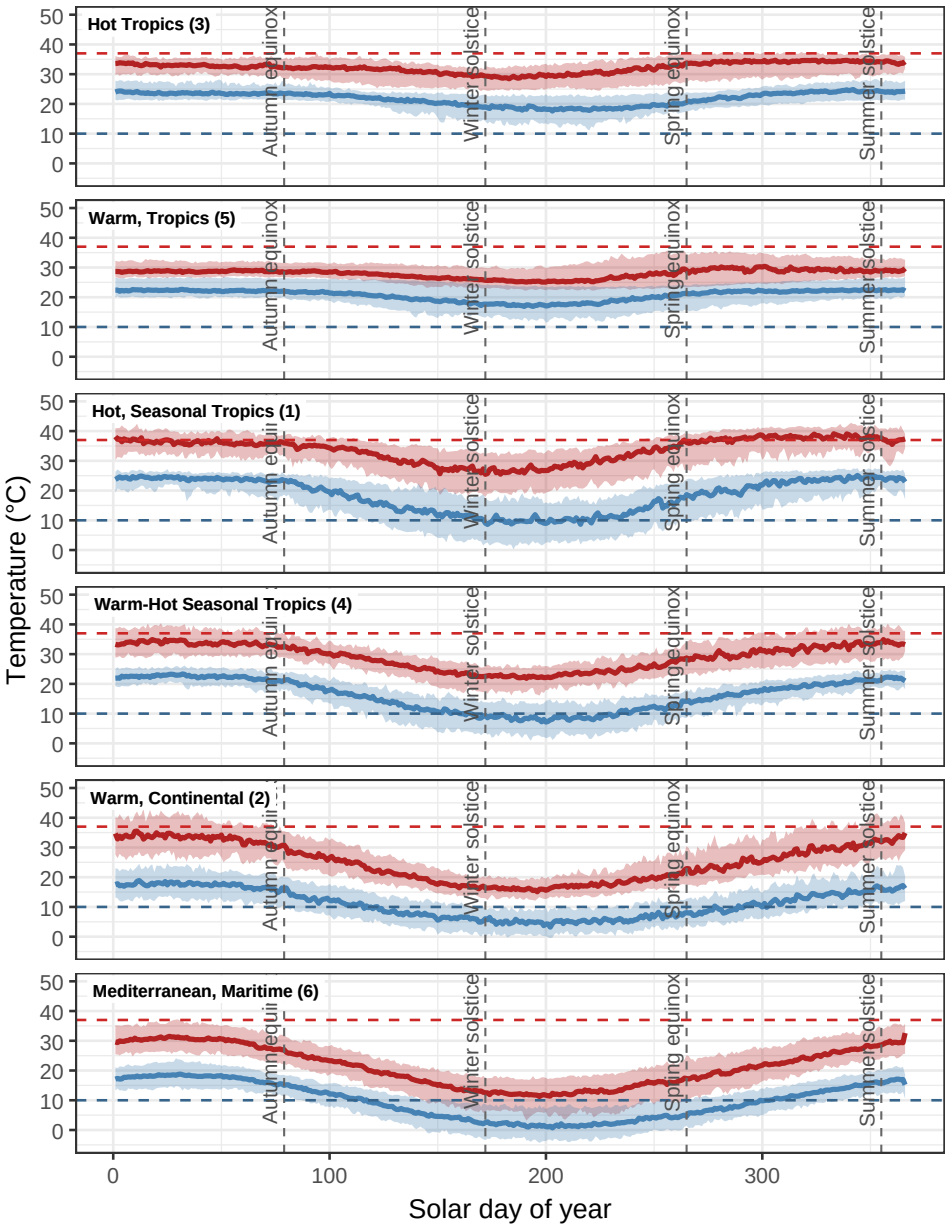


Figure 2.11: Annual minimum and maximum air temperature for the regions defined in Figure 2.6 with the 10 to 90% quantiles. Averaged over the years 2000 to 2025.

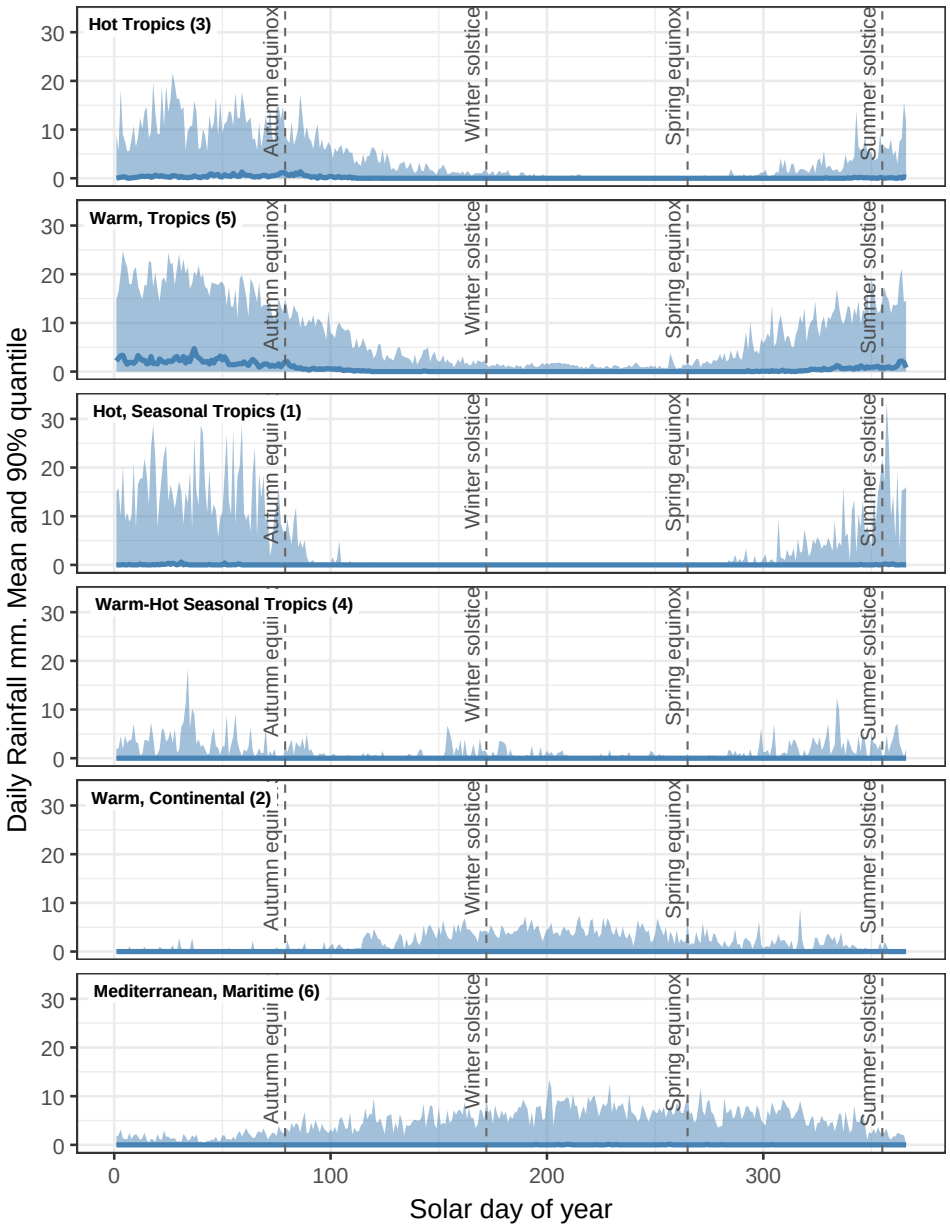


Figure 2.12: Mean daily rainfall for the regions defined in Figure 2.6 with the 10 to 90% quantiles being the light blue lines and the mean, the solid line.

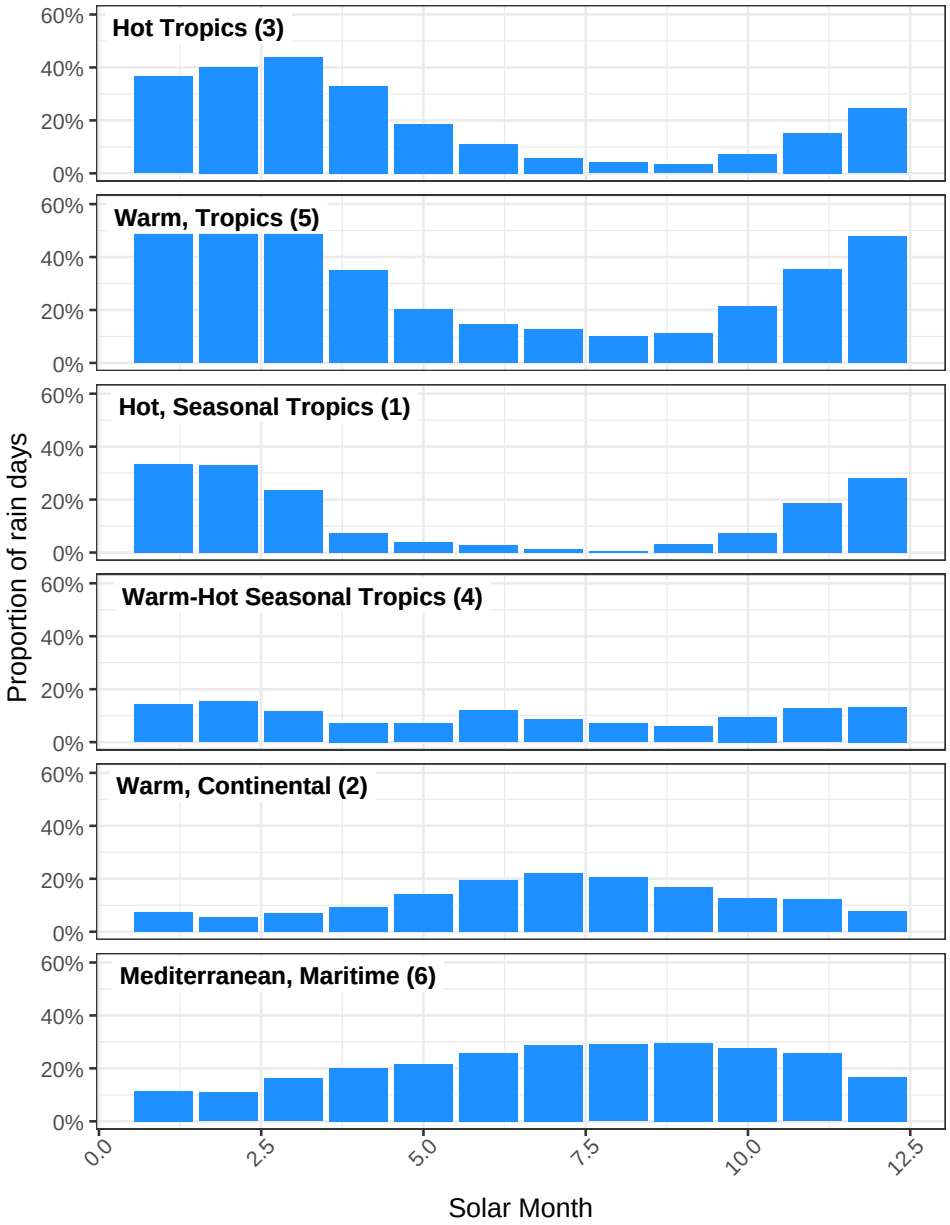


Figure 2.13: Bar chart of the probability of a rainy day in any given month for the regions defined in Figure 2.6.

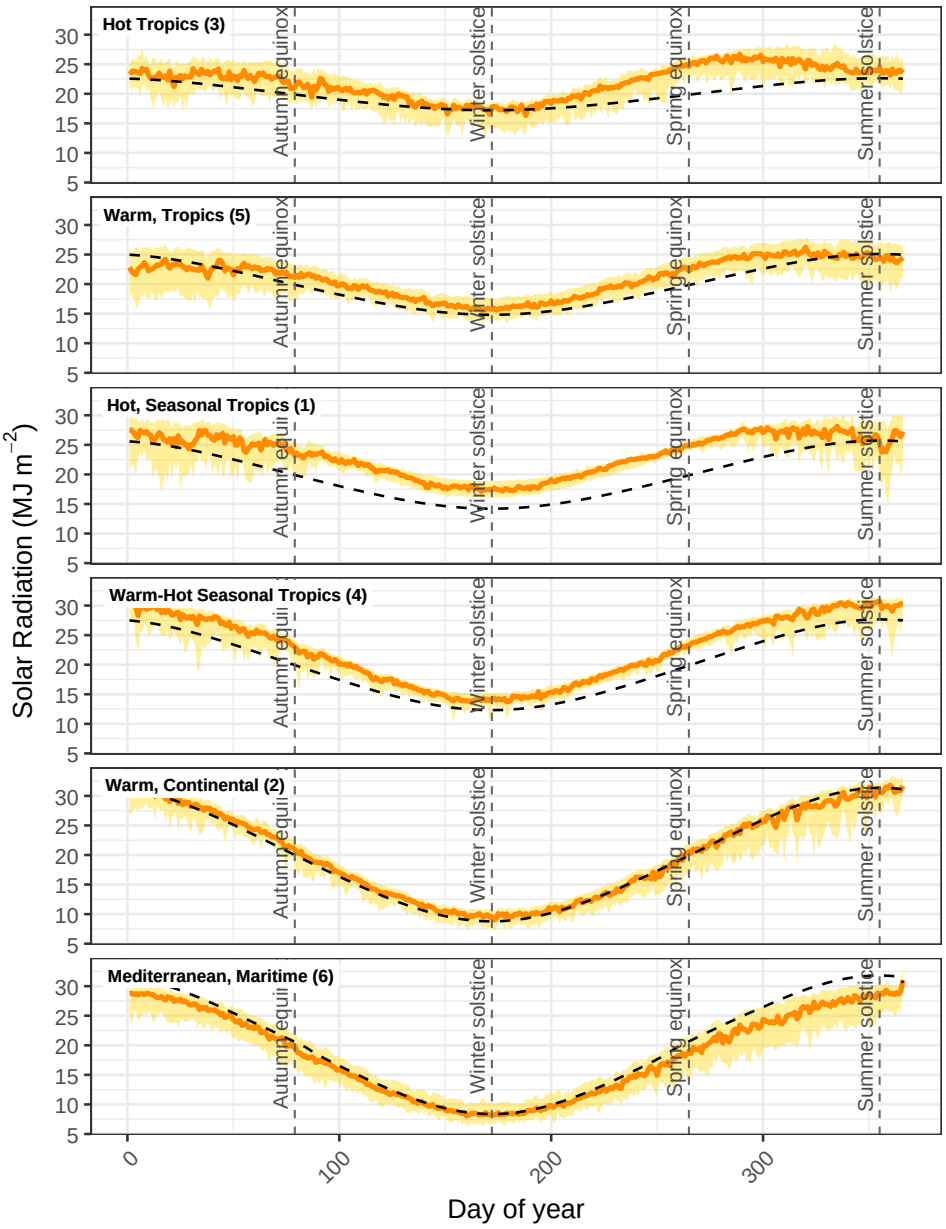


Figure 2.14: Mean and quartiles range for incoming solar radiation for the regions defined in Figure 2.6. The dashed black line represents photoperiod as hours from sunrise to sunset, scale not present.

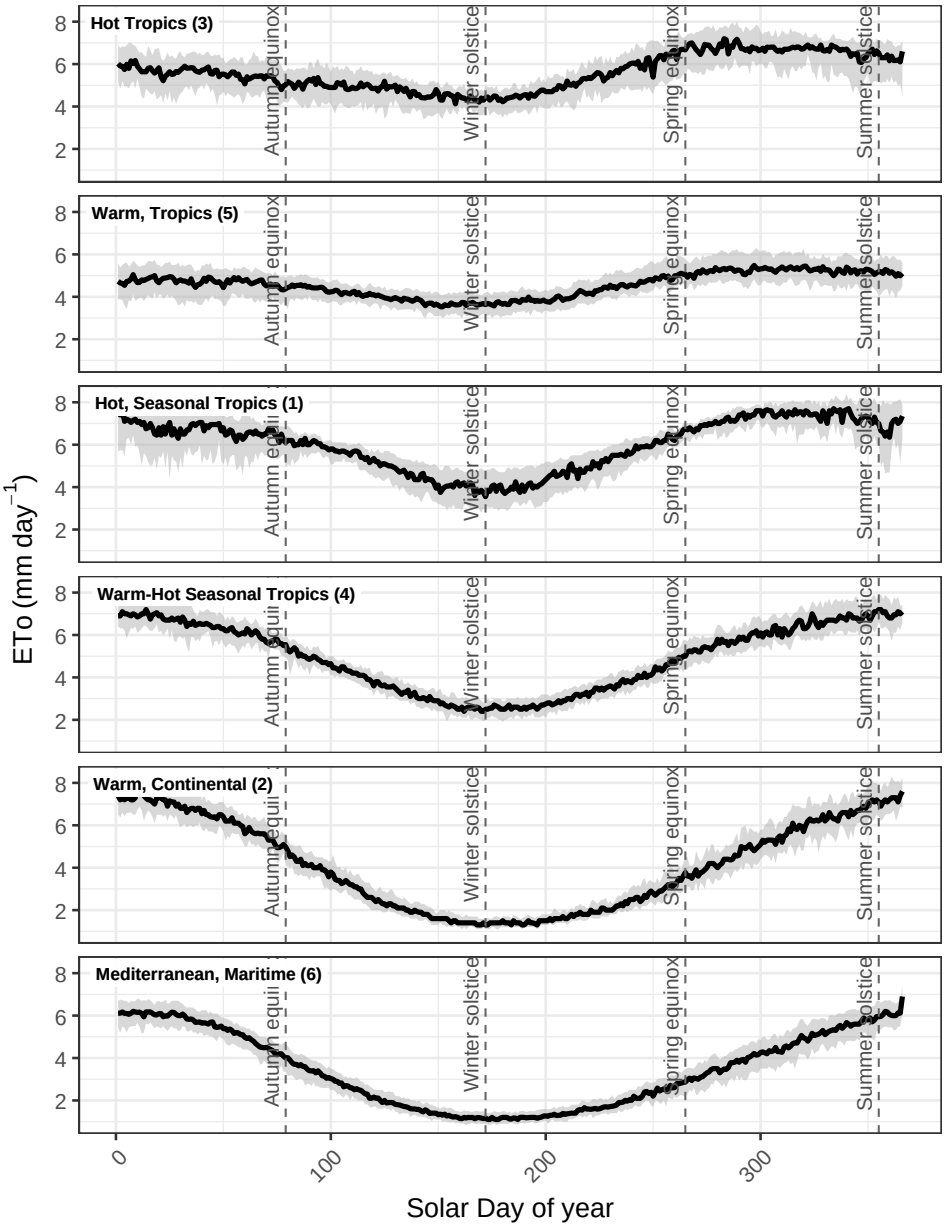


Figure 2.15: Mean and quartile range for daily evapotranspiration (eto, short crop).

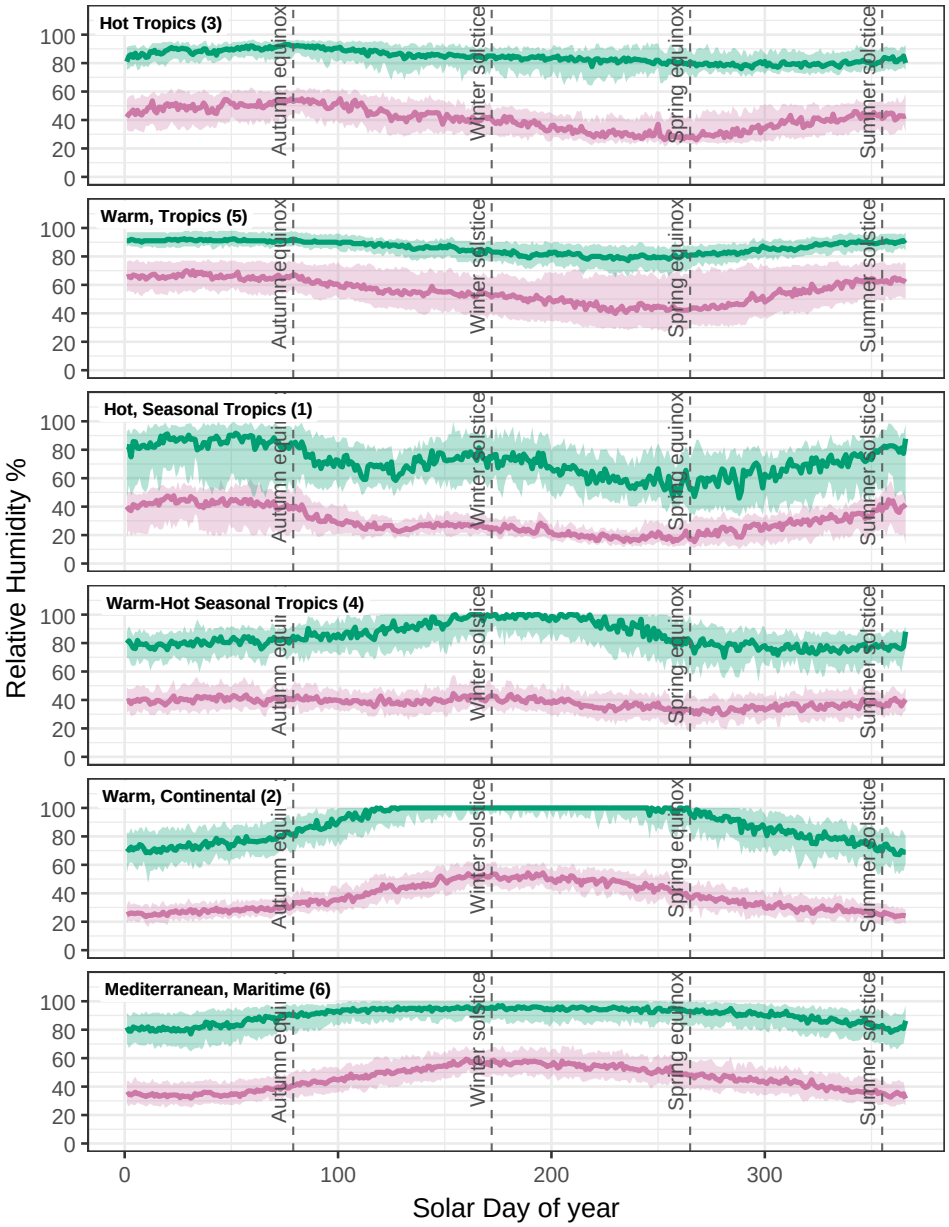


Figure 2.16: Mean and quartile range for the relative humidity at Tmax and Tmin Figure 2.6.

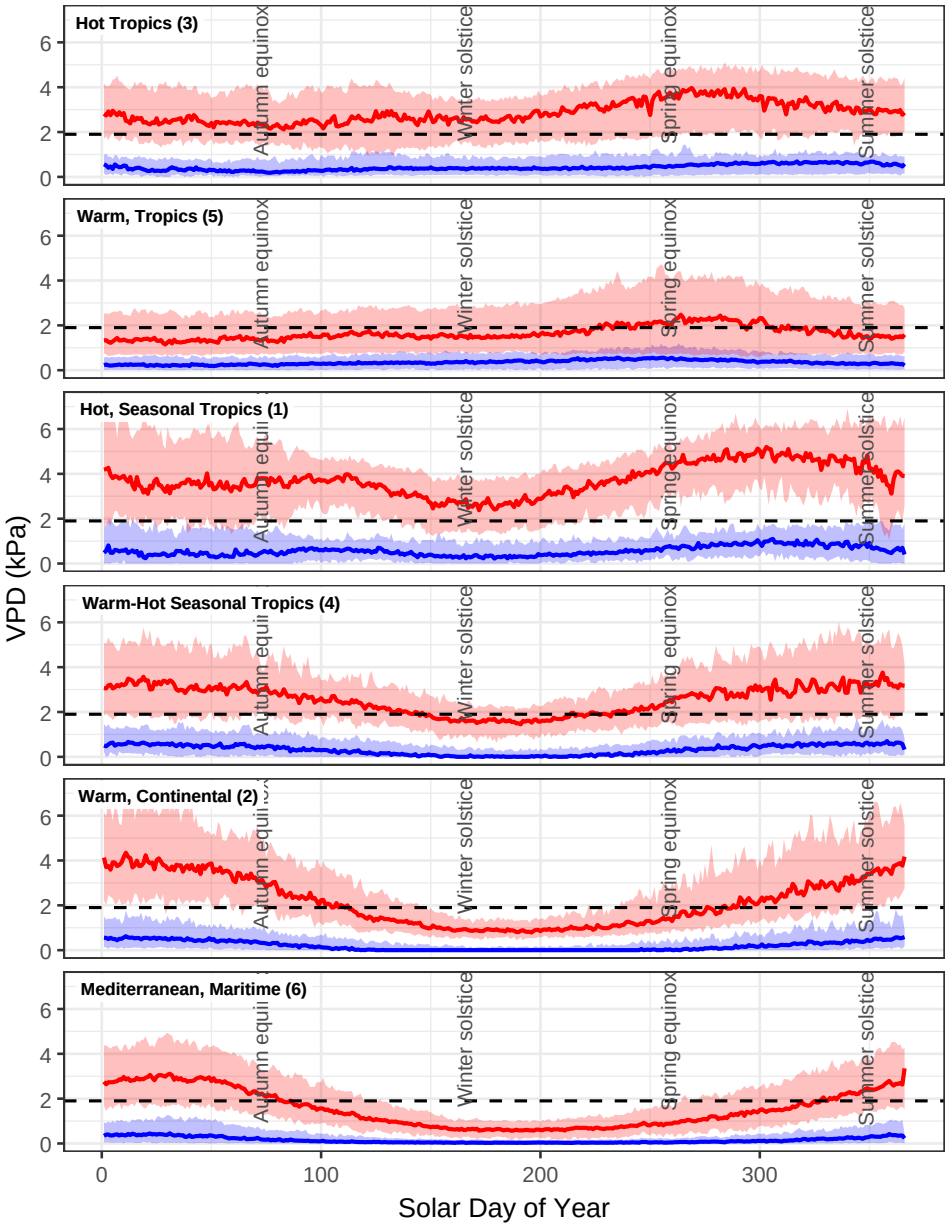


Figure 2.17: Mean and 10:90% quantile range for the mean vapour pressure deficit Figure 2.6.

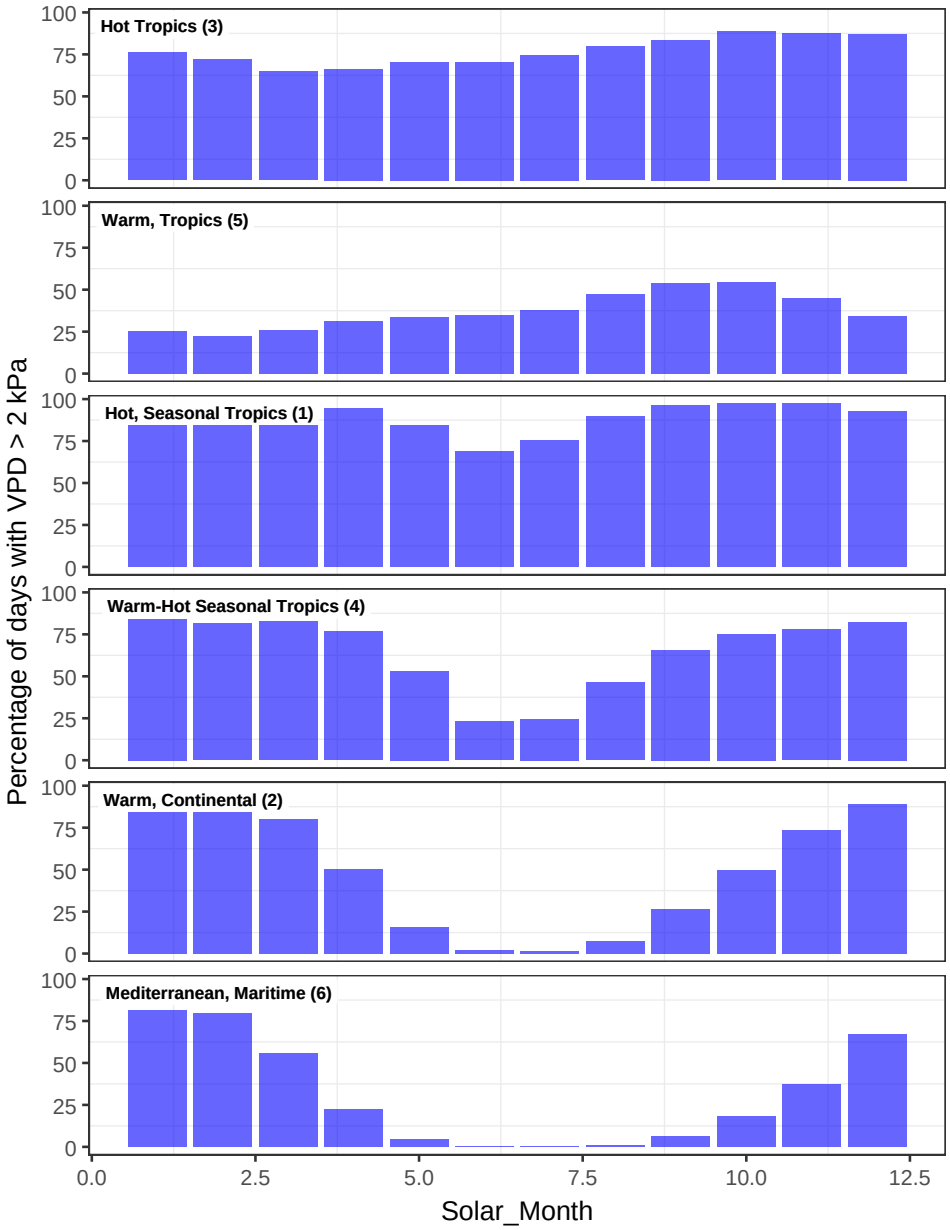


Figure 2.18: Proportion of days in which the vapour pressure deficit exceeds the stress threshold of 2 for each region Figure 2.6.

2.3 Hydrocooling Potential

Experiments demonstrating the effectiveness of canopy cooling have typically been conducted under conditions of substantial heat stress. For example, Greer and Weedon (2014a) applied cooling treatments at approximately 40 °C, while Caravia et al. (2017) used temperatures of approximately 37 °C. Both studies reported significant reductions in canopy temperature and associated improvements in vine function. The physiological basis and practical implementation of canopy cooling are considered in greater detail in Chapter 4. However, the present climate analysis indicates that several of the climate groups identified may benefit substantially from the adoption of hydrocooling systems.

Figure 2.19 shows the difference between dry-bulb (air) temperature and wet-bulb temperature, commonly referred to as wet-bulb depression (Stull, 2011). This metric provides an estimate of the theoretical maximum cooling achievable through evaporation. The Hot Seasonal Tropics group (Kununurra and TiTree) exhibits the greatest evaporative cooling potential, followed by the Warm Continental group during late spring and summer. However, all climate groups, with the exception of the Warm Tropics, display at least moderate cooling potential during part of the year.

An advantage of the wet-bulb depression metric is its simplicity. It can be calculated from readily available weather variables including air temperature, relative humidity and air pressure. In this analysis, T_{max}, RH_{Tmax} and ground-level air pressure were used. Wet-bulb depression may also be compared with the metric adopted by Caravia et al. (2017), which is based on the water-holding capacity of air (kg water kg^{-1} dry air). The correlation between the two approaches exceeds 94%, suggesting that little additional insight is obtained through the more complex thermodynamic calculation. Nevertheless, both remain indirect indicators of cooling effectiveness. A more direct measure would be the temperature of the plant organ beneath an evaporating film of water, as this ultimately determines physiological performance.

Figure 2.20 combines two thresholds, $T_{max} \geq 35$ °C and wet-bulb depression ≥ 8 °C, to estimate the fraction of days on which hydrocooling may provide a meaningful benefit. This approach integrates the effects of temperature, humidity and atmospheric pressure and therefore provides a more realistic comparison among regions.

The analysis suggests that hydrocooling is unlikely to provide sufficient benefit in the Warm Tropics group to justify substantial capital investment. In contrast, the technology appears particularly well suited to the Hot Seasonal Tropics, including locations such as Kununurra and TiTree. Benefits are also likely in the Warm to Hot Seasonal Tropical regions, including Carnarvon and Emerald, and in the Warm Continental production regions of the Murray–Darling Basin.

Table 2.4 presents the average annual number of days over a 26-year period for which hydrocooling conditions were satisfied, together with their year-to-year variability. Approximately two-thirds of years are expected to fall within one standard deviation of the mean. The Warm Continental group is notable for both the high frequency and consistency of suitable cooling conditions, suggesting that returns on investment may be relatively predictable. Greater variability is apparent within the Mediterranean Maritime group, reflecting the inclusion of locations such as Echuca and Gardabani that are climatically more continental despite their statistical grouping with Mediterranean environments.

Overall, the analysis suggests that hydrocooling is most likely to deliver economic benefit in regions that experience frequent combinations of high temperature and low atmospheric humidity. Under such conditions the combination of reduced canopy temperature, improved photosynthetic performance and lower heat stress may provide a substantial productivity advantage.

Table 2.4: Mean annual number of days with Tmax $\geq 35°C$ and WBD $\geq 8°C$.

Climate group	Site	Mean cooling days/year	Std Deviation
Hot Tropics (3)	Limoeiro do Norte	75.4	75.9
Hot Tropics (3)	Petrolina	46.2	22.1
Hot Tropics (3)	Roebuck	67.0	18.8
Warm, Tropics (5)	Diamantino	16.9	24.1
Warm, Tropics (5)	Irece	1.1	3.9
Warm, Tropics (5)	Jales	13.5	19.9
Warm, Tropics (5)	Joao Pinheiro	15.7	14.2
Warm, Tropics (5)	Londrina	5.5	10.1
Warm, Tropics (5)	Mareeba	9.0	5.4
Hot, Seasonal Tropics (1)	Kununurra	195.5	33.7
Hot, Seasonal Tropics (1)	TiTree	123.1	24.7
Warm-Hot Seasonal Tropics (4)	Carnarvon	35.4	12.0
Warm-Hot Seasonal Tropics (4)	Emerald	66.2	25.6
Warm-Hot Seasonal Tropics (4)	St George	66.7	24.1
Warm, Continental (2)	Ar Ramtha	38.7	18.7
Warm, Continental (2)	Ellerslie	49.6	10.7
Warm, Continental (2)	Gingin	39.3	9.4
Warm, Continental (2)	Griffith	39.9	12.1
Warm, Continental (2)	Menindee	64.5	14.4
Warm, Continental (2)	Robinvale	42.7	9.8
Warm, Continental (2)	Sunraysia	43.2	10.5
Warm, Continental (2)	Swan Valley	37.1	8.4
Warm, Continental (2)	Waikerie	41.1	9.0
Warm, Continental (2)	Woorinen	38.1	9.8
Mediterranean, Maritime (6)	Applethorpe	2.1	2.6
Mediterranean, Maritime (6)	Canicatti	9.3	9.7
Mediterranean, Maritime (6)	Coolup	17.8	5.4
Mediterranean, Maritime (6)	Echuca	27.3	9.2
Mediterranean, Maritime (6)	Gardabani	25.8	13.3
Mediterranean, Maritime (6)	Iori	3.9	4.2
Mediterranean, Maritime (6)	Kanafar	1.6	2.8
Mediterranean, Maritime (6)	Taanayel	5.1	5.0

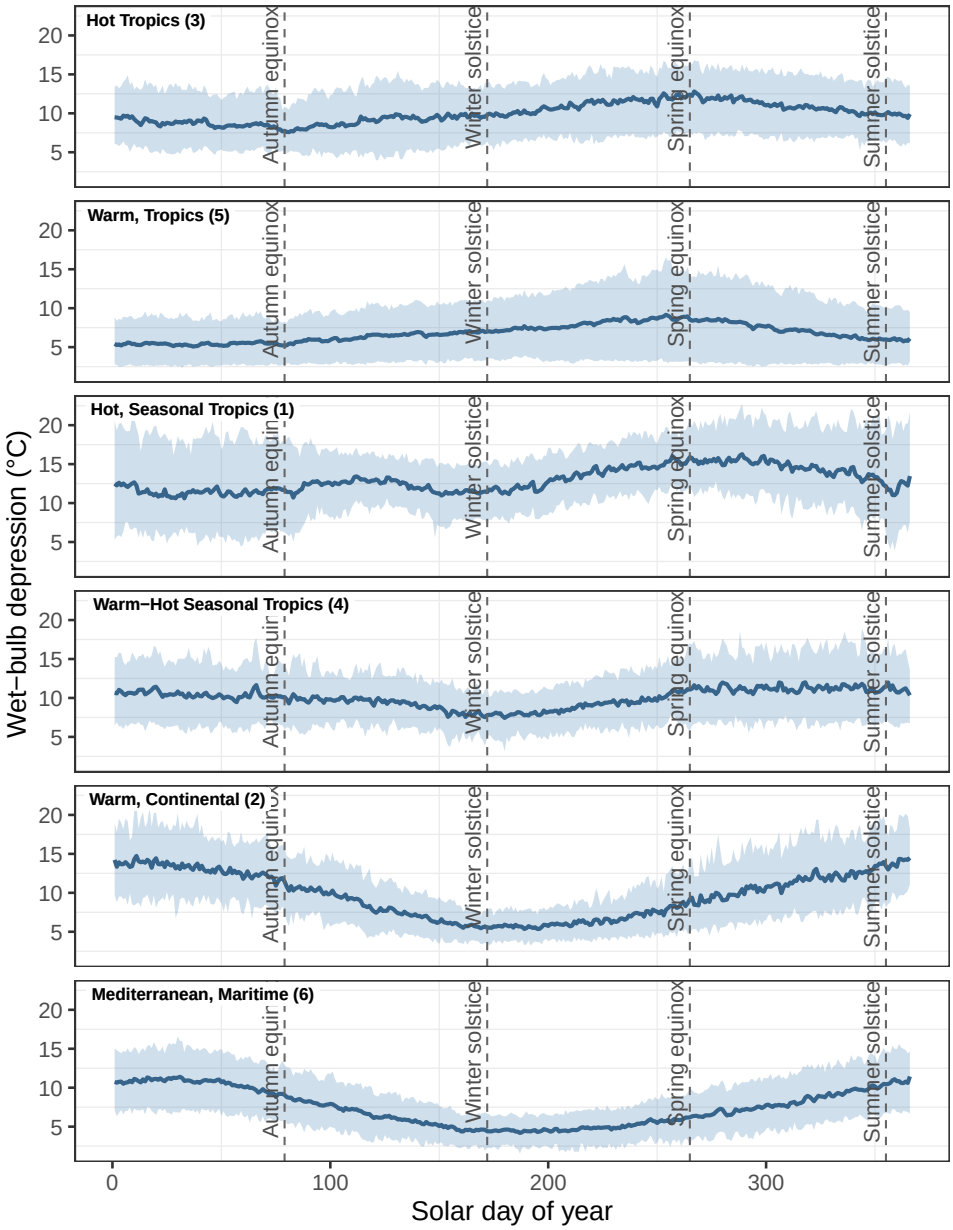


Figure 2.19: Mean (solid line) and 90% quantile (shaded ribbon) of potential for evaporative cooling reduction in air temperature (Stull, 2011).

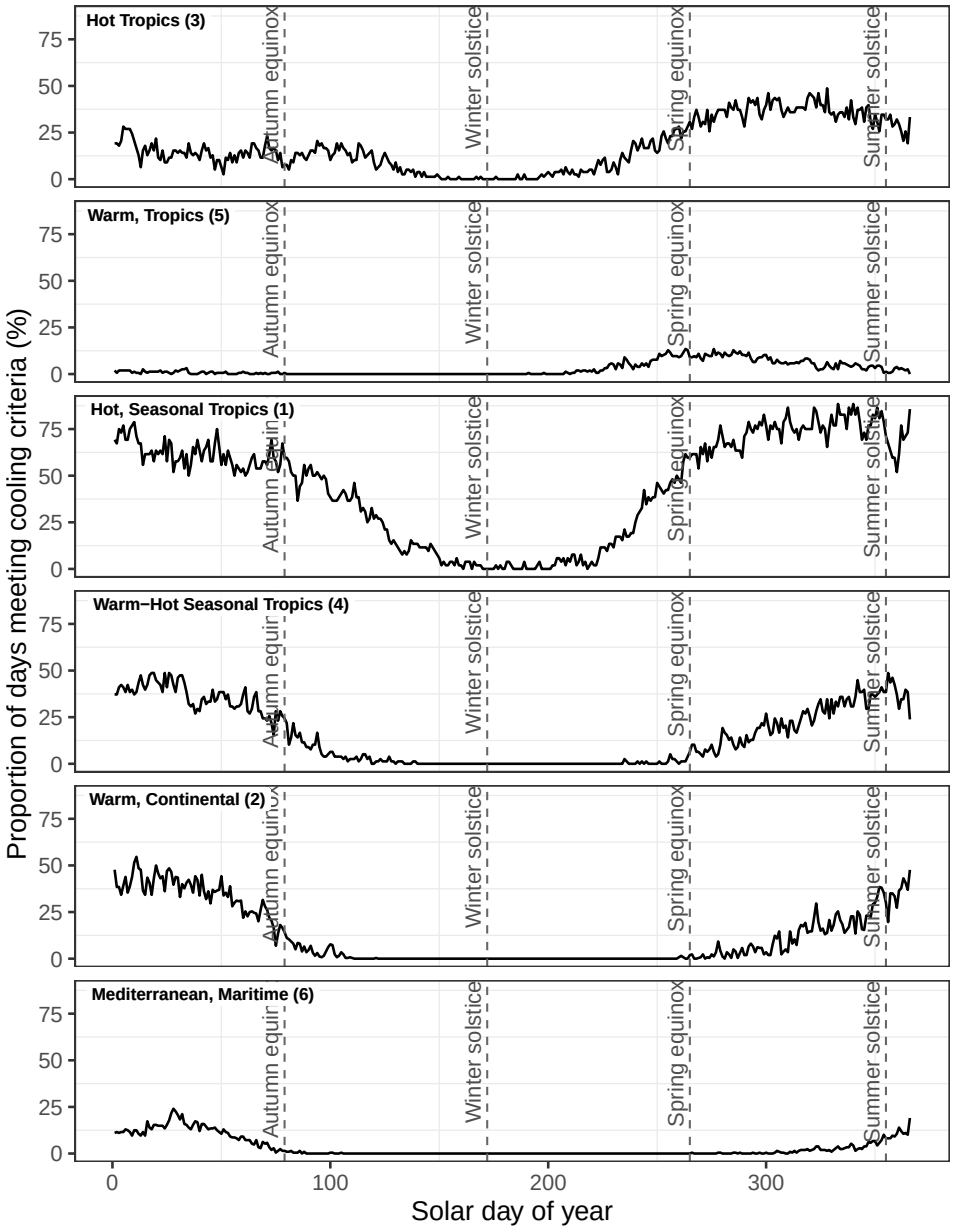


Figure 2.20: Daily frequency of days in which field hydrocooling should produce benefits for vine function (Tmax $\geq 35\,^{\circ}\mathrm{C}$ and wet bulb depression (WBD) $>8\,^{\circ}\mathrm{C}$), *e.g.* photosynthesis.

Chapter 3

Climatic constraints to table grape production in northern Australia

3.0.1 Summary

Temperature-related effects were identified as the dominant climatic constraints to table grape productivity in tropical and subtropical regions. While much published research focuses on the direct impact of high temperature on photosynthesis, the consequences are considerably broader. Elevated temperatures influence reproductive development, assimilate partitioning, reserve accumulation and respiratory losses. Of these, the exponential increase in respiration with temperature is suggested to represent the most important limitation to productivity. High temperatures also affect inflorescence initiation and development, although these effects can be partly mitigated through cultivar selection and appropriate management practices.

Summary of Key Constraints

The principal environmental factors constraining table grape productivity in low-latitude regions are:

- Elevated temperatures above approximately $32\,^{\circ}\mathrm{C}$ may substantially reduce inflorescence initiation and development, despite moderate warmth generally favouring floral induction.
- Temperatures above approximately $20\,^{\circ}\mathrm{C}$ during budburst may reduce secondary inflorescence ramification, thereby limiting bunch size.
- Cultivars differ markedly in their ability to initiate and develop inflorescences under warm climatic conditions. Cultivar selection should therefore draw on local experience or data from climatically similar production regions.
- Temperatures exceeding approximately $30\,^{\circ}\mathrm{C}$ during flowering and fruit set may reduce fruit set and ultimately yield.
- Berry size tends to decline progressively as temperatures exceed approximately $25\,^{\circ}\mathrm{C}$.
- The relatively constant daylength of low-latitude environments promotes extended or continuous vegetative growth. This increases competition for assimilates between active growth and reserve accumulation.
- Reduced accumulation of reserve carbohydrates limits the capacity for vigorous and productive regrowth following pruning.
- High temperatures reduce net carbon gain both through direct effects on photosynthesis and, more importantly, through exponentially increasing respiratory losses.
- Warm night temperatures are common in low-latitude environments, particularly in coastal regions. Elevated night temperatures increase respiratory losses in both shoots and roots and are likely to represent a significant constraint on productivity.
- High soil temperatures may alter growth partitioning, favouring shoot growth at the expense of root growth and reserve accumulation.
- Root systems constitute the principal storage organ for carbohydrates supporting the subsequent growth cycle. Reduced root growth or reserve accumulation therefore has consequences extending beyond the current season.
- Low reserve status, or inefficient mobilisation of reserves, combined with vigorous vegetative growth may contribute to bunch shedding following budburst.

- Preliminary results from the current project suggest that utilisation of root starch reserves may be lower in tropical and subtropical production regions than in traditional temperate regions.

3.1 Introduction

This section reviews the climatic factors that may limit grapevine productivity and that require management if productivity is to be improved. The information presented here provides the physiological framework for the subsequent analysis of climatic conditions in Australia's table grape production regions. While numerous publications address aspects of grapevine stress physiology, most are focused on traditional production environments and the wine industry rather than table grape production in tropical and subtropical climates (Ollat et al., 2019; Rogiers et al., 2022; Sinha et al., 2025; Venios et al., 2020).

3.1.1 Benchmark climatic zones for successful table grape cultivation

The natural habitat of the wild progenitor of the cultivated grapevine extends around the margins of the Mediterranean Basin, within maquis vegetation (comparable in some respects to the kwongan heathlands of southwestern Australia), and throughout river valleys and broad-leaved forests extending across Spain, France, Morocco, Italy, Germany, Turkey, Greece, Georgia, the regions surrounding the Black and Caspian Seas, and the Near East as far as Turkmenistan, Afghanistan and Tajikistan (Zohary, 1995). This distribution spans approximately 33 to 47° N, a latitudinal range equivalent in Australia to a band extending from Harvey, Western Australia, southward beyond Tasmania.

Consequently, the grapevine family encompasses taxa adapted to a wide range of climatic conditions, from warm coastal environments with winter-dominant rainfall to warm-temperate continental climates. However, most members remain susceptible to severe winter injury, with temperatures below approximately $-8\,^{\circ}\mathrm{C}$ often proving lethal. Grapevines are typical deciduous plants of the Northern Hemisphere, with annual growth cycles strongly regulated by temperature and photoperiod, and possibly by diurnal temperature variation. These responses are expressed through the dormancy cycle, a fundamental adaptation that synchronises growth and reproduction with seasonal environmental conditions (Considine and Considine, 2016).

Evidence from genomic studies suggests that domesticated table grapes (*Vitis vinifera* subsp. *sativa*) most likely originated in the Levant, probably in the Beqaa Valley of present-day Lebanon (Dong et al., 2023). Current evidence supports an independent domestication event from that which occurred in the Caucasus and subsequently provided the foundation for the wine industry through selection from the wild grapevine, *Vitis vinifera* subsp. *sylvestris*. These domestication events occurred approximately 11,000 years before the present, near the beginning of the Holocene epoc.

The Holocene followed the global retreat of continental ice sheets and was characterised by the establishment of a relatively stable climate. This period also coincided with the emergence of agriculture and permanent human settlement. It is therefore reasonable to regard the Levantine region as providing a useful benchmark for the climatic conditions under which cultivated grapevines evolved and were first domesticated.

3.2 The Focus

Tropical environments present a suite of challenges for viticulture arising not only from high temperatures but also from elevated humidity and an increased risk of extreme rainfall and wind events. The present analysis focuses primarily on grapevine physiology and therefore does not consider in detail environmental hazards that operate independently of the vine's inherent biological limitations, even though they may substantially affect production.

Nevertheless, disease pressure remains a critical consideration because warm, humid conditions strongly favour the development of fungal and bacterial pathogens. Consequently, commercial table grape production within the tropics is generally concentrated in arid or semi-arid regions where disease risk is reduced. In some countries, notably Brazil, breeding programmes have focused on incorporating disease resistance from tropical grapevine species into cultivated germplasm, thereby improving adaptation to low-latitude environments (*e.g.* Leão et al., 2019).

3.3 The Normal Growth Cycle

3.4 Adaptation

Much research on grapevine stress physiology, and plant stress physiology more generally, has focused on short-term responses to environmental extremes such as heat waves (Caravia Bayer, 2016; Gouot-Davoust et al., 2026) and episodes of water-deficit stress (Cogato et al., 2022; Palliotti et al., 2014). However, as climate change progresses, increasing attention is being directed towards the capacity of plants to adapt to sustained changes in environmental conditions (Crous et al., 2022; Slot et al., 2014). The physiological and genetic basis of adaptation in grapevines has been reviewed by Ollat et al. (2019),

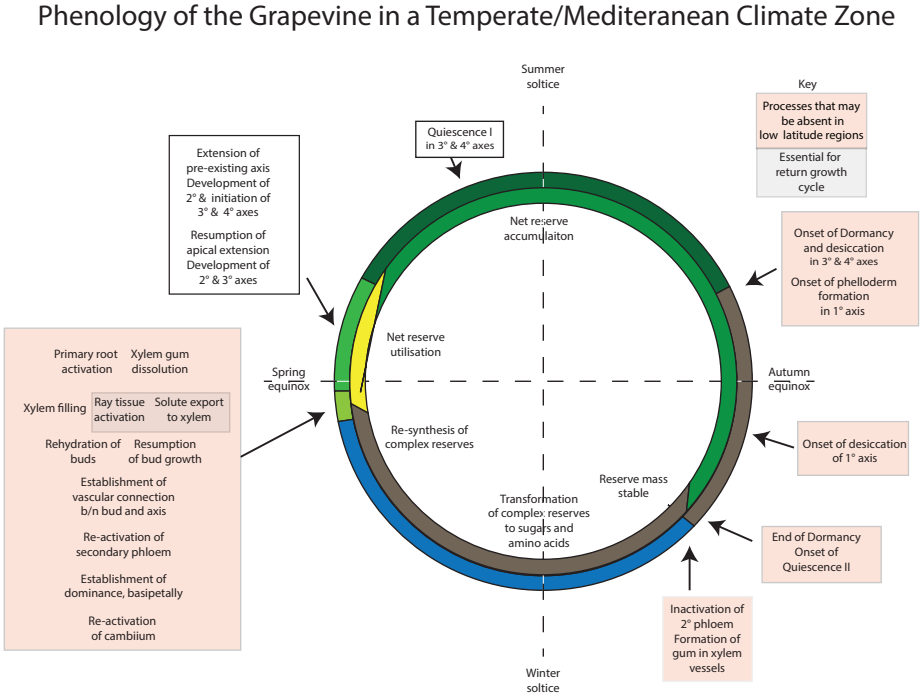


Figure 3.1: A diagram illustrating the sequence of processes that occur in grapevines growing under standard conditions. The coloured boxes are those that probably do not occur under conditions favouring continuous or near-continuous growth in tropical and subtropical regions.

primarily in the context of water-use efficiency, although other adaptive responses have also been considered (Rogiers et al., 2009).

In the context of cultivating perennial plants beyond their region of origin, adaptation cannot be reduced to a single trait. Rather, successful adaptation requires coordinated responses across multiple developmental, physiological and reproductive processes. Figure 3.1 illustrates key developmental and phenological events associated with grapevine adaptation to its ancestral environment. Many of these processes are absent, disrupted or only weakly expressed in low-latitude environments characterised by continuous or near-continuous growth.

Two of the principal environmental signals to which grapevines are adapted, photoperiod and low temperature (Alleweldt, 1957; Fennell et al., 2005; Hackbarth and Scherz, 1935), are largely absent in tropical environments. Adaptation to climatic gradients commonly occurs through the development of ecotypes that are genetically differentiated along environmental clines (*e.g.* Borchert et al., 2005). Within the Vitaceae, adaptation across a broad range of climates has occurred over evolutionary timescales. Species of *Vitis* are found in environments ranging from regions experiencing winter temperatures below $-50\,^{\circ}\mathrm{C}$ to tropical Central America. Individual species, however, generally occupy a much narrower climatic niche.

Recognising this limitation, Brazilian grapevine breeding programmes have sought to broaden the adaptive base of cultivated grapevines through hybridisation with tropical grape species (Fennell, 1948). Such work aims to introduce traits associated with disease resistance and adaptation to warm climates into germplasm derived largely from *Vitis vinifera* (Leão et al., 2019). The genetic improvement of grapevines for tropical adaptation is, however, beyond the scope of this review. Instead, the focus here is on identifying the principal climatic constraints affecting productivity within managed viticultural systems. Agronomic practices that may ameliorate these constraints are considered separately.

From a production perspective, adaptation is ultimately expressed through effects on carbon acquisition, carbon balance, growth partitioning and yield formation. These provide a useful framework for evaluating the constraints imposed by low-latitude environments.

The primary constraints affecting productivity can be grouped into four broad categories:

- **Gross assimilation**
  - Light intensity
  - Duration of illumination
  - Gas exchange
  - Canopy architecture
- **Net assimilation**
  - Respiratory losses
  - Photosynthetic electron transport efficiency
  - End-product inhibition arising from excess carbohydrate accumulation
- **Partitioning of growth**
  - Allocation to reproductive versus vegetative growth
  - Photoperiod effects (primarily on shoots and leaves)
  - Apical dominance
  - Day–night temperature relationships
  - Soil temperature
  - Reserve carbohydrate status
  - Nutritional status
  - Rootstock–scion interactions
  - Agronomic practices
- **Yield formation**
  - Inflorescence initiation and development
  - Secondary inflorescence ramification during budburst
  - Fruit set
  - Plant water status, particularly between flowering and veraison

Only those factors that are particularly relevant to low-latitude cultivation are considered in detail. Water-deficit stress, for example, occurs in viticultural regions across all latitudes and is therefore not treated comprehensively here. Similarly, nutritional limitations are largely outside the scope of this review, although interactions between nutrient acquisition and the elevated soil temperatures characteristic of tropical and subtropical environments warrant further investigation.

3.5 Light Duration, Intensity and Quality

Light is the ultimate source of energy for plant growth. Although sunlight is universally available, its intensity, daily duration, seasonal variation and spectral quality vary substantially with latitude (Figures 3.2 and 3.3. Table grapes are among the most widely cultivated fruit crops globally and are grown across a broad latitudinal range extending from equatorial to temperate regions (FAO-OIV, 2016), approximately 0 to 50°. One of the most important environmental gradients across this range is photoperiod. In grapevines, photoperiod influences extension growth and contributes to the onset of dormancy in latent buds (Considine and Considine, 2016).

3.5.1 Photoperiod

Dormancy in grapevines comprises at least two related but distinct processes. The first is true bud dormancy, characterised by desiccation of the latent bud and increased resistance to freezing injury (Ait Barka et al., 1995). This process begins in late summer and is closely associated with the cessation of shoot extension growth (Figure 3.2).

The second process, although less frequently discussed outside the freezing-tolerance literature, involves broader maturation of the perennial structure of the vine. Chilling promotes stem maturation and suberisation, leaf senescence and abscission, partial dehydration of perennial tissues, occlusion of phloem sieve tubes by callose (Esau, 1948), and blockage of xylem vessels by arabinogalactan gums (Price et al., 2015; Sun et al., 2008). Together, these changes contribute to the transition from active growth to a quiescent state adapted for winter survival.

There is no evidence that dormancy is an absolute requirement for completion of the grapevine life cycle. Rather, it appears to represent a flexible response to local environmental conditions. In low-latitude environments where neither short days nor prolonged cool temperatures occur, pruning alone is often sufficient to stimulate budburst through the removal of apical dominance. Furthermore, the response to photoperiod is not binary. As locations approach the critical day length, intermediate responses occur, as demonstrated by comparisons between regions such as Carnarvon and the Swan Valley (Velappan et al., 2023).

Nevertheless, continuous or near-continuous growth appears to have physiological consequences. In environments such as Carnarvon and Emerald, assimilates continue to be directed towards active vegetative growth rather than storage. This may reduce the accumulation of reserve carbohydrates required to support regrowth following pruning.

The absence of a prolonged dormant period therefore creates potential competition between vegetative growth and reserve accumulation. Reduced storage of starch and other reserve carbohydrates may limit the vigour of subsequent growth cycles. In grapevines, assimilate partitioning is largely determined by sink demand (Gamalei, 1989; Turgeon and Medville, 1998). During most of the growth cycle, carbohydrates move preferentially towards actively growing tissues, whereas during post-veraison ripening sugars are actively accumulated in berries through the action of SWEET-family sugar transporters (*e.g.* Ren et al., 2020).

Early growth following pruning depends heavily upon stored reserves, particularly those located in roots and perennial woody tissues. These reserves provide much of the carbon required for initial growth and remain important until approximately flowering, after which current photosynthesis progressively assumes a greater role in supporting development (Bates et al., 2002; Bennett et al., 2005; Winkler and Williams, 1945).

The absence of a true dormant period may also influence apical dominance. Under temperate conditions, seasonal interruption of phloem transport contributes to resetting shoot growth and facilitating more uniform budburst in the following season (Esau, 1948). In environments where phloem function remains largely uninterrupted, mechanisms that normally reduce apical dominance may be less effective, potentially contributing to uneven budburst and excessive vegetative growth.

Conclusion

The absence of a strong photoperiod signal in low-latitude environments promotes continued vegetative growth and reduces the allocation of assimilates to reserve storage. As a consequence, the reserve base available to support growth following pruning may be diminished, contributing to lower productivity and reduced crop reliability.

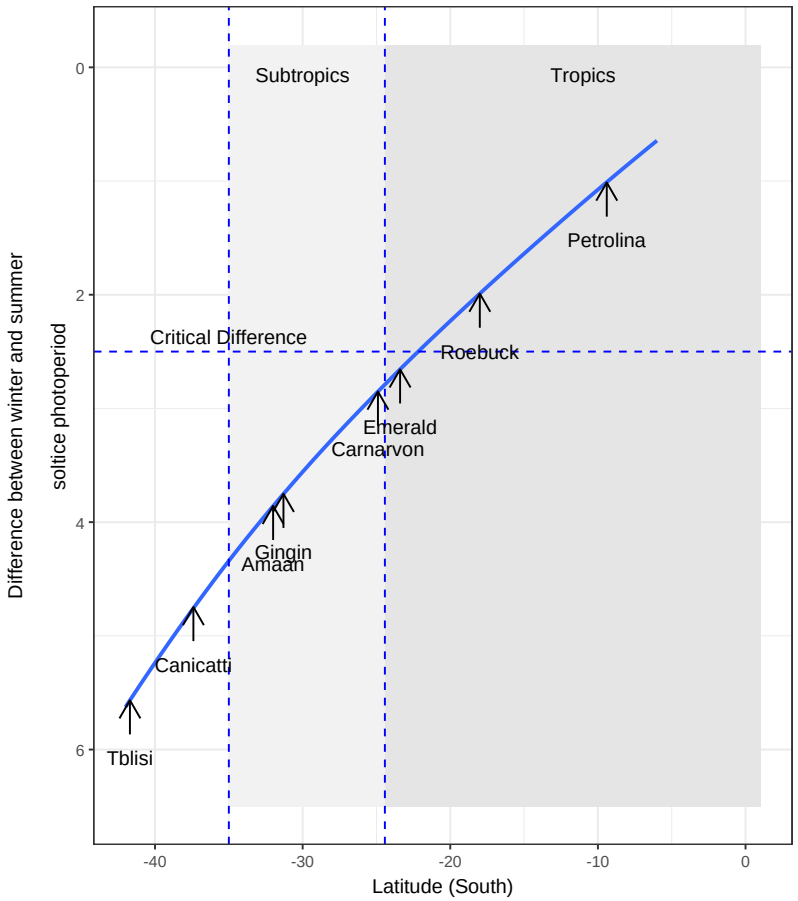


Figure 3.2: Plot of the change in day length, dawn to dusk, from winter solstice to summer solstice against latitude with some key location plotted. The horizontal line represents the approximate critical difference required to initiate latent bud dormancy (Fennell and Hoover, 1991).

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3.5.2 Light Quality and Intensity

Photosynthetic assimilation is determined by a range of climatic and edaphic factors including light intensity, light quality, temperature, atmospheric vapour pressure deficit and soil water availability. Grapevines perceive and respond to these

factors both immediately through physiological regulation and over longer timescales through acclimation. Stomata are widely recognised as key integrating organs linking plant water status, atmospheric conditions and photosynthetic performance (Medrano et al., 2002). Soil water potential is a major determinant of plant water potential and consequently of stomatal conductance and carbon assimilation (*e.g.* Tombesi et al., 2015). However, because irrigation is generally managed in commercial production systems, soil water status is not considered further in this review.

Most published studies describing the effects of light on grapevine photosynthesis have employed single-leaf light response curves. While useful mechanistically, such measurements do not adequately represent the behaviour of an entire vineyard canopy (Intrieri et al., 1997). Using whole-canopy gas exchange measurements, these authors demonstrated that canopy photosynthesis saturates at irradiances approximately 1.5 times greater than those observed for individual leaves, while maximum net canopy assimilation is approximately half that measured at the leaf level (Fig. 3.4). Consequently, although exposed leaves may become light saturated, shaded leaves deeper within the canopy continue to contribute substantially to carbon gain.

Solar radiation is rarely limiting in cultivated vineyards. Typical values are of the order of 25 to 30 MJ m^{-2} day^{-1}. Approximately 48% of this energy lies within the photosynthetically active radiation (PAR) waveband (400–700 nm). Solar radiation is conventionally expressed as energy integrated over wavelengths from approximately 300 to 3000 nm, whereas PAR refers only to the photosynthetically active portion of the spectrum. Furthermore, solar radiation is measured in units of energy (J or MJ), while PAR is more appropriately expressed as photon flux density because photosynthesis depends on the number of photons absorbed rather than their total energy content. Although these quantities are not directly interchangeable, empirical conversion factors permit approximate comparison. Figure 3.3b therefore partitions incoming solar radiation into PAR and non-PAR components on an energy basis.

Figure 3.3a illustrates that total annual radiation varies relatively little across the latitudinal range in which table grapes are cultivated. Seasonal variation is substantial, particularly at higher latitudes, but integrated annual radiation differs much less than might be expected from day-length considerations alone. Consequently, radiation availability itself is unlikely to be a major determinant of regional suitability for table grape production, despite pronounced seasonal differences in radiation supply (*c.f.* Figure 3.3b).

Very high irradiance levels, typically exceeding approximately 1500 $\mu mol\ m^{-2}\ s^{-1}$, may induce photoinhibition and transient impairment of the photosynthetic apparatus, particularly when combined with water deficit, heat stress or prior exposure to low night temperatures (*e.g.* Bertamini et al., 2006; Bertamini and Nedunchezhian, 2003; Bertamini et al., 2007; Correia et al., 1990). However, such effects are generally reversible, are restricted primarily to highly exposed leaves, and occur across the full latitudinal range of grape cultivation. They therefore do not represent a specific constraint associated with low-latitude production.

Conclusion

Differences in solar radiation availability across the latitudinal range of commercial table grape production are relatively small. While excessive irradiance may occasionally induce photoinhibition in exposed leaves, light intensity is rarely a primary limitation to productivity in tropical and subtropical production systems.

3.5.3 Air and Organ Temperature

High-temperature damage to the photosynthetic apparatus is generally of greater consequence to grapevine productivity than high irradiance alone. For example, transferring potted vines from a 25/15°C day/night regime to 40/25°C resulted in a 35% reduction in photosynthesis that required approximately 12 days for recovery (Greer and Weston, 2010). When such heat stress was imposed at veraison, assimilation was reduced sufficiently to impair fruit ripening.

Although leaf temperature and air temperature are usually strongly correlated, the relationship is modified by factors such as leaf exposure, canopy shading and plant water status (Millar, 1972). A recurring challenge in the literature is that emphasis is commonly placed on air temperature, whereas the temperature directly affecting physiological processes is organ temperature, particularly leaf temperature. Where possible, these two variables should therefore be distinguished.

Evaporative cooling is a critical mechanism protecting leaves from thermal damage under conditions favouring heat stress. This process has been quantified and modelled in grapevines (Greer, 2012). Even under conditions of high vapour pressure deficit (VPD), where stomatal closure would ordinarily be expected, transient and spatially heterogeneous stomatal opening may occur to facilitate evaporative cooling and prevent excessive leaf temperatures (Downton et al., 1988). The capacity for stomatal regulation under heat stress exhibits both adaptive plasticity and heritable variation across plant species (Sinha et al., 2025; Wang et al., 2026) and is well documented in grapevines (*e.g.* Faralli et al., 2022; Millar, 1972; Schultz, 2003a).

The detrimental effects of high temperatures on the photosynthetic apparatus, particularly above approximately 35 °C, are well established (*reviewed by* Berry and Bjorkman, 1980). However, the temperature optimum for photosynthesis is not fixed

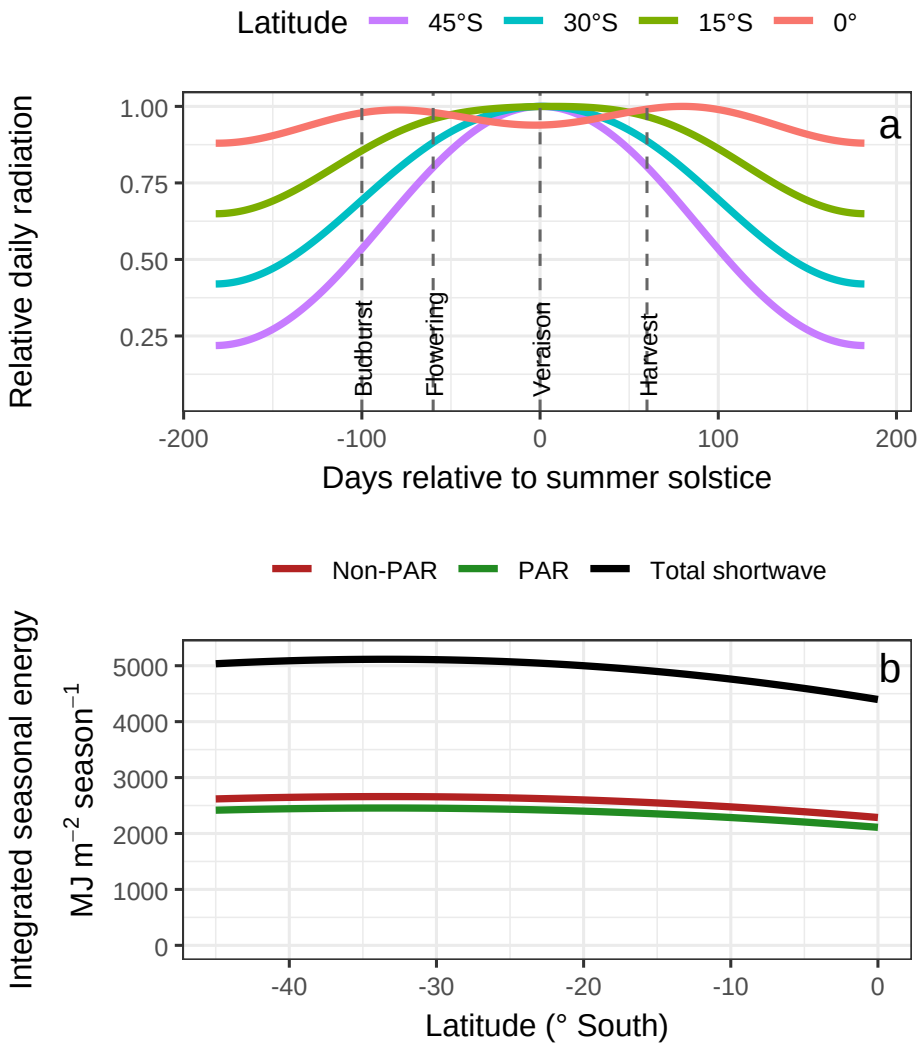


Figure 3.3: a. Change in daily radiation relative to the summer solstice and for particular latitudes. b. Change in total incoming solar radiation, PAR estimated as 0.48 total solar radiation and remainder (thermal energy).

and depends in part on the thermal environment experienced during growth (*e.g.* Yamasaki et al., 2002). This acclimation response enables plants to maintain photosynthetic function under warmer conditions. In grapevines, and in C_3 species more generally, maximum photosynthetic rates are commonly observed at approximately 30 °C, although prolonged exposure to high temperatures may shift the optimum towards 35 °C (*e.g.* Greer, 2017; Yamasaki et al., 2002).

Figure 3.5 illustrates the effects of leaf temperature on net assimilation, respiration and stomatal conductance in vines growing in a hot-climate environment in the Riverina region of New South Wales (Greer, 2017). The two cultivars studied differ markedly in their apparent capacity to maintain photosynthetic activity at elevated temperatures, with assimilation maxima differing by approximately 2 to 3°C. The cultivars also differ in stomatal regulation. Such differences may be associated with variation in hydraulic behaviour and water-deficit sensitivity, including the continuum between isohydric and anisohydric responses (Lovisolo et al., 2010; Pou et al., 2012; Schultz, 2003b). The decline in stomatal conductance observed at high temperatures is largely attributable to increasing atmospheric evaporative demand, expressed as vapour pressure deficit.

Conclusion

Temperatures above approximately 35 °C progressively impair photosynthetic function, particularly during prolonged exposure. Temperatures exceeding 40 °C may cause persistent damage to the photosynthetic apparatus and substantially reduce productivity, while temperatures approaching or exceeding 50 °C become increasingly injurious and may ultimately prove lethal.

3.6 Factors Affecting Net Assimilation

Net carbon gain reflects the balance between photosynthetic assimilation and respiratory losses. In the context of tropical and subtropical viticulture, the principal climatic constraints affecting net assimilation are elevated respiration rates and reductions in photosynthetic efficiency at high temperature. A third limitation, end-product inhibition, may occur when carbohydrate export from leaves is restricted, but this phenomenon is not specific to low-latitude environments and may arise equally in temperate regions under conditions of high temperature or phosphorus limitation (McClain and Sharkey, 2019).

Figure 3.5b illustrates the strong relationship between respiration and temperature. Re-analysis of the data of Greer (2017) suggests a $Q_{10} \approx 2$, implying that respiration approximately doubles for every $10\,^{\circ}\mathrm{C}$ increase in temperature (Table 3.1; *cf.* Zufferey et al., 2000). While these measurements represent respiratory losses measured concurrently with photosynthesis in leaves, respiration occurs continuously throughout the vine, including roots, shoots, trunks and fruit (Escalona et al., 2012).

Respiration represents a substantial sink for assimilated carbon. Estimates suggest that 30 to 60% of photosynthetically fixed carbon may be respired, with up to 75% of whole-plant respiratory losses arising from the root system (Escalona et al., 2012; Torregrosa et al., 2017). Consequently, increases in temperature can substantially reduce net carbon gain, even when photosynthesis remains positive. Elevated temperatures therefore affect productivity not only through direct effects on photosynthesis but also through increased maintenance costs associated with living tissues.

Night temperature is particularly important because respiratory losses continue in the absence of photosynthesis. Both the magnitude and duration of warm night temperatures influence the capacity of grapevines to accumulate reserves and biomass (Figure 3.6). This relationship has been demonstrated experimentally and under field conditions (*e.g.* Zufferey et al., 2000). In the comparison presented in Figure 3.6, the estimated proportion of fixed carbon lost through respiration was approximately 49% at the coastal site compared with 36% at the inland site. These observations are consistent with studies showing that roots are the dominant contributors to whole-plant respiration, exceeding the respiratory demands of either the trunk or canopy (Medrano et al., 2015).

The importance of root respiration suggests that soil temperature may be as important as air temperature in determining whole-vine carbon balance. Warm soils increase metabolic activity within the root system and therefore increase the proportion of assimilated carbon required for maintenance respiration.

Conclusion

Elevated day and night temperatures increase respiratory losses throughout the vine, particularly within the root system. Consequently, warm climates and warm soils may substantially reduce net carbon gain, reserve accumulation and productivity, even when photosynthetic rates remain relatively high.

Table 3.1: Respiration relative to that at $25^{\circ}\mathrm{C}$ based on re-analysis of data provided by Greer (2017).

Temperature $^{\circ}\mathrm{C}$	Relative respiration
15	0.5
20	0.71
25	1.0
30	1.42
35	2.01
40	2.84

3.7 Soil Temperature and the Diurnal Temperature Range

The root system is frequently overlooked because it is hidden from view and difficult to observe or measure non-destructively. Nevertheless, it is a critical component of the grapevine, providing access to water and mineral nutrients, forming beneficial associations with soil microorganisms, particularly mycorrhizal fungi, and, in natural systems, providing mechanical support.

The grapevine root system has been reviewed by Smart et al. (2006), who concluded that soil conditions are the primary determinant of root distribution. However, they also noted substantial differences in root biomass among genotypes and the unusual propensity of grapevines to develop deep root systems, generally within the unsaturated zone above the water table. The natural habitat of the wild grapevine is nevertheless riparian, occupying riverine environments that may be subject to periodic flooding (*e.g.* Arnold et al., 2017).

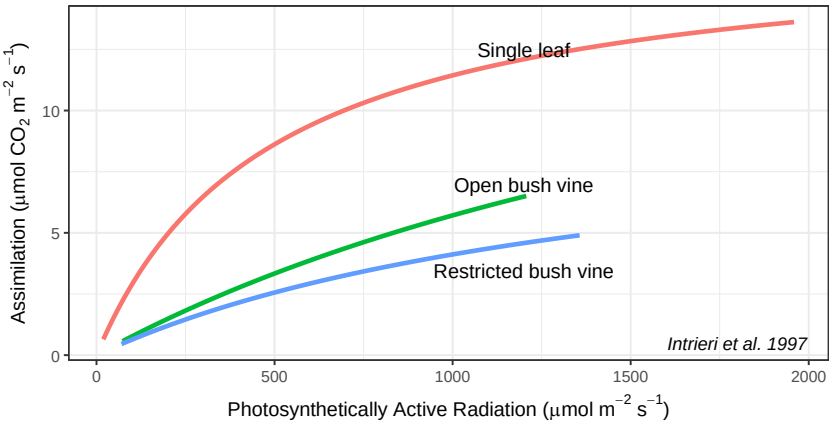


Figure 3.4: Comparison of the relationship between the level of photosynthetically active radiation (c. 400 to 700 nm) when measured on single leaves, an open, sprawling canopy or a restrained (positioned) canopy. Data from Intrieri et al. (1997).

The significance of the root system often becomes apparent only when root growth is constrained by factors such as root-restricting soils, nematodes, pathogenic fungi or physical barriers. The importance of maintaining a balance between root and shoot growth has been demonstrated in several classic studies using peach seedlings (Richards, 1978; Richards and Rowe, 1977a,b). Root pruning or restriction of root volume produced a corresponding reduction in shoot growth, indicating a tight physiological coupling between the above- and below-ground components of the plant. Application of cytokinin to leaves largely restored shoot growth despite root restriction, suggesting that cytokinins produced by the root system play an important role in regulating shoot development and maintaining root–shoot balance.

Root growth and the root:shoot ratio are strongly influenced by temperature (Figure 3.8). Increasing root-zone temperature generally promotes shoot growth more strongly than root growth, resulting in a progressive increase in the shoot:root ratio. A similar experiment using one-year-old Cabernet Sauvignon rootlings showed a marked reduction in inflorescence development at a root temperature of 35 °C, although root biomass itself was not measured (Zelleke and Kliewer, 1979). Shoot growth increased strongly over the temperature range studied, resulting in approximately a four-fold increase in the shoot:root ratio between 20 °C and 30 °C.

The contrasting growth responses of roots and shoots are noteworthy. While shoot growth increased exponentially with temperature, root growth increased only modestly. This response closely resembles that induced in peach seedlings by exogenous cytokinin application (Richards, 1978; Richards and Rowe, 1977a), suggesting that elevated root temperatures may alter hormonal regulation of biomass partitioning in favour of vegetative growth.

These experimental treatments extend beyond the range of conditions normally encountered in vineyards and should therefore be interpreted cautiously. For example, field observations indicate that mean soil temperatures at a depth of 200 mm generally approximate mean air temperatures (Figure 3.7). Nevertheless, the implications for perennial crops are important. Additional vegetative growth produced in response to warm soils is largely removed during pruning, whereas root biomass persists and serves as a principal storage organ for reserves required during the subsequent growth cycle. A shift in biomass accumulation away from roots and towards shoots therefore potentially reduces the long-term capacity of the vine to store and remobilise carbohydrates and nutrients.

Negative effects of elevated soil temperature on root development have also been observed in grapevines by several investigators (Field et al., 2009, 2020; Kubota and Shimamura, 1989; Mahmud et al., 2018). However, there appear to be no published comparisons of root:shoot ratios or root biomass from commercial vineyards across a latitudinal gradient extending into tropical and subtropical production regions. This represents a significant gap in understanding the causes of the tropical productivity gap.

Conclusion

Elevated soil temperatures may shift biomass partitioning towards vegetative growth and away from root growth. Because roots constitute a major storage organ for carbohydrate reserves, a high shoot:root ratio may indirectly reduce productivity by limiting reserve accumulation and the capacity for vigorous growth in subsequent production cycles.

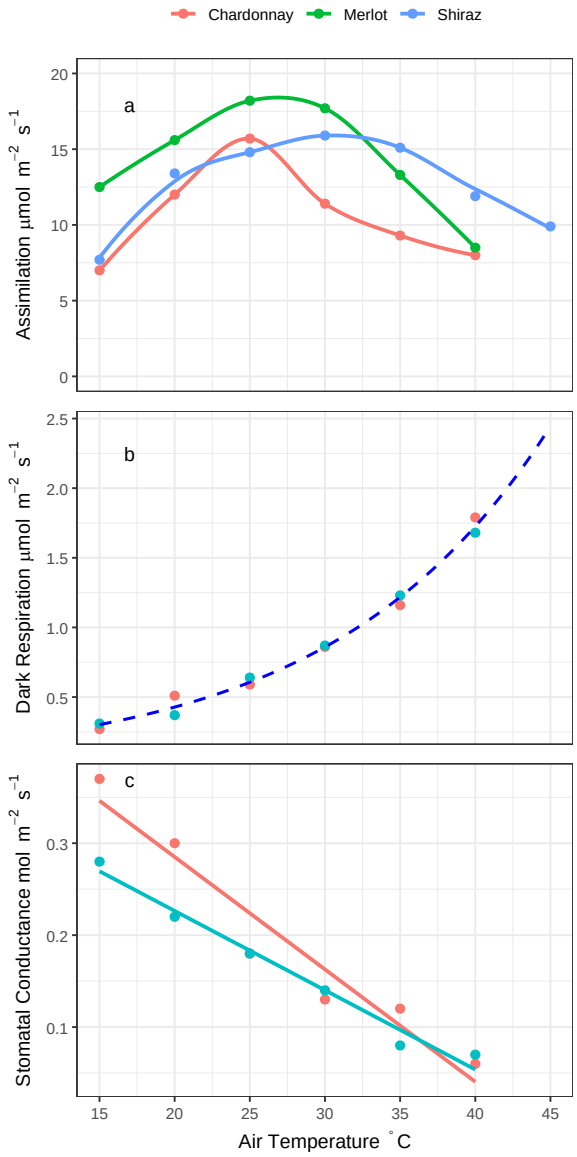


Figure 3.5: The effect of air temperature on three aspects of leaf function: a, assimilation; b, respiration and c, stomatal function. The dashed line in b, represents an exponential curve of the form $R = 0.606 \times 2.008^{(T-25)/10}$, a Q_{10} function. Data replotted from (Greer, 2017, 2022).

3.8 Inflorescence Initiation and Development

It has long been recognised that temperature influences inflorescence initiation and development in grapevines (reviewed by Buttrose, 1974; Huglin, 1958; May, 2000; Srinivasan and Mullins, 1981; Watt et al., 2008). Moderate temperatures generally favour reproductive development, and the processes leading from an undifferentiated primordium to a fully developed inflorescence have been studied in considerable detail (Noyce et al., 2019; Olivain and Bessis, 1986a,b). Nevertheless, poor inflorescence initiation and development remain important constraints to productivity in tropical and subtropical production regions (Dahal et al., 2019, 2022; Leão and Da Silva, 2003b; Oag et al., 1996).

Research conducted by the CSIRO Division of Horticultural Research demonstrated that inflorescence initiation is strongly influenced by both light intensity and temperature (*e.g.* Buttrose, 1969). Figures 3.9 and 3.10a indicate an optimum temperature for inflorescence initiation and development of approximately 30 °C, with reproductive development declining progressively at higher temperatures. It is noteworthy that cultivars differ markedly to temperature and to light. Sultana and Ohanez producing few inflorescences under the conditions while Rhine Riesling and Muscat show strong responses to temperature and light. The temperature response range is however narrow, generally < 20° to 30°C. Independent studies conducted in California reached similar conclusions (Figure 3.10b). Many of the tropical and subtropical regions evaluated in this study regularly experience temperatures in the upper thirties and low forties during the critical period of initiation and development.

The practical effect of these influences is illustrated in Figure 3.11, which compares bud fruitfulness of four cultivars grown in the São Francisco Valley of Brazil with equivalent data from California and northern Victoria. Bud fruitfulness in the tropical environment was consistently lower, with only 'Maroo Seedless' approaching the levels observed in more traditional production environments. These observations indicate that the response is strongly genotype-dependent and that cultivar selection is likely to be an important component of successful tropical viticulture.

Figure 3.10a illustrates the scale of the influence and opportunity available through the exploitation of genetic diversity within *V. vinifera* for fruitfulness. Shoot vigour is also positively correlated with inflorescence formation, suggesting that the two processes may be influenced by common physiological factors (Olivain and Bessis, 1988).

Under temperate conditions, inflorescence development typically requires approximately 90 to 100 days (Buttrose, 1969; May, 1964). Development may proceed more rapidly under tropical conditions owing to the accelerated effects of temperature on growth and differentiation. Inflorescence initiation itself is determined largely by environmental conditions at the time anlagen are formed at the shoot apex. However, sensitivity to environmental conditions persists for at least the following three weeks (Buttrose, 1974; May, 1964; Palma and Jackson, 1981).

The importance of short-term weather conditions was demonstrated by Baldwin (1964), who showed that fruitfulness of developing buds of 'Sultana' was strongly associated with temperatures between approximately 28 °C to 32 °C and low cloudiness. His analysis suggested that climatic effects on bud fruitfulness were concentrated within a developmental window of approximately three weeks following initiation. It is important to note, however, that this work addressed inflorescence initiation rather than subsequent development. This research has been extended in new Zealand, confirming the importance of temperature prior to flowering as the most important yield determining, climatic variable (Zhu et al., 2020). However, there as in the Baldwin (1964) study, temperature tended to be suboptimal rather than excessive.

Leaves are typically initiated at intervals of approximately two to three days at the shoot apex (*e.g.* Schultz, 1993). Axillary buds and the associated dormant bud complex develop shortly thereafter, at a stage when the subtending leaf has separated from the apical meristem by approximately 10 mm (Palma and Jackson, 1981). Consequently, successive nodes enter their period of greatest sensitivity to environmental conditions at intervals of approximately two to three days. This is randomly distributed among buds on a vine, and thus should be viewed as a continuous process.

Conceptually, buds occupying nodes 1 to 10 are therefore likely to be sensitive to climatic conditions from approximately one week after budburst until four weeks later, with some sensitivity potentially extending for a further three weeks (Buttrose, 1974). Consequently, taking into account, the post initiation process, elevated temperatures may influence reproductive development for a substantial proportion of the growth cycle tropical and subtropical regions.

Conclusion

Although moderate temperatures favour inflorescence initiation and development, prolonged exposure to temperatures above approximately 32 °C appears to reduce bud fruitfulness in many cultivars. Evidence from tropical and subtropical production regions suggests that impaired inflorescence development is a major contributor to reduced productivity, although substantial genetic variation exists and some cultivars appear considerably more resilient than others.

3.8.1 Primary Bud Necrosis (PBN)

Primary bud necrosis (PBN) is a physiological disorder that occurs throughout grape-growing regions worldwide and can substantially reduce bud fruitfulness and productivity (Collins and Rawnsley, 2004). The adaptive significance of the phenomenon remains uncertain, although it may represent an evolved mechanism that suppresses excessive branching in a forest liane until favourable canopy conditions are attained. Such a hypothesis is consistent with the strong requirement for high light intensity during inflorescence initiation and development.

Shading is widely regarded as the principal environmental factor associated with PBN. Consequently, conditions or management practices that promote excessive canopy vigour and internal shading are commonly implicated. These include high vegetative vigour (Dry and Coombe, 1994; Lavee, 1987; Wolf and Warren, 1995), excessive nitrogen supply (Kliewer et al., 1994; Perez Harvey and Valdes Laursen, 1989), and elevated gibberellin activity (Collins and Rawnsley, 2008; Lavee et al., 1993). High temperatures may also exacerbate the response by stimulating vegetative growth and increasing canopy density. Although PBN is often associated with vigorous vines, observed incidences may occasionally exceed 75% of primary buds (Considine and Considine, unpublished data). Such levels, however, are not restricted to tropical environments and have also been reported from major production regions such as Davis, California (Morrison and Iodi, 1990).

Primary bud necrosis is regarded as a major limitation to productivity in tropical double-cropping systems (Camargo, 2007; Fan et al., 2023). Extended periods of cloudiness can aggravate the condition through promotion of excessive vigour and canopy shading, particularly in seedless cultivars (Camargo, 2007). The disorder develops during bud formation, typically from around flowering onwards, and is characterised by localised cell death followed by isolation of the affected tissue from the remainder of the bud (Fan et al., 2023; Morrison and Iodi, 1990).

Management strategies focus primarily on reducing excessive vigour and improving canopy light penetration. These include canopy management practices, judicious nitrogen fertilisation, and in some circumstances the application of growth-retarding compounds (*e.g.* Rawnsley and Collins, 2005).

Conclusion

Primary bud necrosis is likely to represent an important risk factor in tropical and subtropical production systems. Conditions that favour excessive vegetative growth, including high temperatures, prolonged periods of cloudiness, high nitrogen availability and certain cropping systems, appear to increase the incidence of the disorder and may contribute substantially to reduced bud fruitfulness and yield.

3.8.2 Inflorescence Growth During and Following Bud Burst

The mature latent bud contains only the basic framework of the future inflorescence (Pouget, 1981, reviewed earlier work). Most elaboration of the inflorescence and development of individual flowers occurs during the period immediately preceding and following bud burst (reviewed by Buttrose, 1974; Morrison, 1991; Srinivasan and Mullins, 1981; Vasconcelos et al., 2009). Consequently, climatic conditions during this period may have a substantial influence on final flower number and bunch size.

Flower number per inflorescence has been shown to be sensitive to temperature during bud burst. Dunn and Martin (2000) reported a strong relationship between flower number and the thermal conditions prevailing during this stage of development, while late pruning, which delays bud burst into warmer conditions, reduced flower number (Bouard, 1966; Dunn and Martin, 2000). Direct heating of individual buds also reduced flower number (Petrie and Clingeleffer, 2005), while heating of whole vines reduced flower number by as much as 40% (Eltom et al., 2017). In the latter study, the mean increase in temperature was only 2.1 °C; however, temperature extremes were substantially greater, occasionally approaching 40 °C. These deleterious responses have been proposed to arise as a consequence of a change in partitioning, further benefitting vegetative growth at the expense of reproductive (Tombesi et al., 2022).

Relatively little research has examined the role of resource availability during this phase of development. One notable example is the work of Eltom et al. (2014), who demonstrated that restricting assimilate supply through cane cincturing during early shoot growth induced abortion of developing inflorescences. Also shading has been shown to induce a disorder termed Early Bunch Stem Necrosis which occurs later in the development of the inflorescence in cool climate regions of wine grape production (Jackson, 1991). That also is associated with limited resource availability. The sensitivity of inflorescences to resource limitation is also well known in propagation studies, where considerable manipulation is often required to prevent abortion of floral primordia during development (Mullins and Rajasekaran, 1981; Mullins, 1968; Ollat et al., 1998).

Inflorescence abortion, bunch shedding and severe deformation are common observations in tropical and subtropical production systems. These disorders are likely to arise because developing inflorescences are relatively weak sinks for assimilates and therefore compete poorly with rapidly growing shoots. In environments that favour vigorous vegetative growth, elevated temperatures potentially reduce reserve availability, reproductive structures may fail to obtain sufficient resources to complete development (Figure 3.12).

The competitive relationship between vegetative and reproductive sinks is illustrated by the partitioning studies of Edson et al. (1995), summarised by Howell (2001) (Figure 3.13). Changes in sink strength markedly alter the allocation of assimilates among shoots, fruit and roots. This observation is particularly relevant to tropical and subtropical viticulture where elevated temperature favours vegetative growth and may reduce both carbohydrate reserves and reproductive development.

Conclusion

The period immediately before and after bud burst is critical for determining final flower number and inflorescence size. Elevated temperatures reduce flower development, while limited assimilate availability may result in partial or complete inflorescence abortion. The combination of vigorous shoot growth and reduced reserve availability characteristic of many tropical and subtropical production systems is likely to exacerbate these losses.

3.8.3 Pollination and Fruit Set

The grapevine is predominantly self-fertile and self-pollinating, although wind-assisted pollination may contribute to fruit set. Consequently, pollination itself is rarely a significant limitation to productivity except in cultivars with functionally female flowers (*e.g.* 'Ohanez').

Fruit set, however, is highly sensitive to the balance between assimilate supply and demand. The grapevine operates within a finely balanced source–sink system in which developing inflorescences compete directly with rapidly growing shoots for carbohydrates and mineral resources. Cap fall occurs approximately midway through the log-linear growth phase of shoot

development. Since the capacity of an organ to attract assimilates depends largely on its relative growth rate, the small inflorescence is often at a competitive disadvantage compared with the vigorously growing shoot. Consequently, any disruption of assimilation, translocation or reserve mobilisation may have serious consequences for fruit set (Coombe, 1959, 1962, 1965).

Water-deficit stress and heat stress are two of the most common causes of poor fruit set. Their effects arise principally through reductions in assimilate supply at a stage when the inflorescence depends heavily on current photosynthesis. Stored reserves are near their seasonal minimum during flowering and fruit set, making reproductive development particularly sensitive to environmental stress (Winkler and Williams, 1945). The susceptibility of grapevines to water-deficit stress is greatest during the flowering to fruit-set period (Hardie and Considine, 1976), whereas sensitivity during ripening is comparatively low.

High temperature may also directly impair fruit set. In a controlled-environment study, transfer of flowering vines from a $25/15^{\circ}$C to a $40/25^{\circ}$C day/night regime for only four days completely eliminated fruit set (Greer and Weston, 2010). Exposure of vines to the same temperature treatment at either veraison or mid-ripening caused a cessation of berry expansion but did not have the catastrophic effect observed during flowering. Although these treatments represented acute temperature shocks imposed on non-acclimated vines, they demonstrate the vulnerability of flowering and fruit set to extreme temperature events.

Earlier studies similarly reported progressive reductions in both berry number and berry size as temperature increased above approximately $25\,^{\circ}$C (Figure 3.14) Kliewer (1977)). More recently, Merrill et al. (2020) reported that fruit set declined rapidly once temperatures exceeded approximately $30\,^{\circ}$C, suggesting that even moderate increases above the optimum may have important effects on yield.

The effects of water deficit and heat stress are likely to be additive. Both reduce assimilate availability to developing inflorescences while simultaneously increasing the competitive advantage of vegetative sinks. Consequently, poor fruit set in tropical and subtropical environments may reflect not only direct damage to reproductive processes but also disruption of the underlying balance between assimilate supply and demand.

Conclusion

Fruit set is highly sensitive to both water deficit and high temperature. Temperatures exceeding approximately $30\,^{\circ}$C *to* $35\,^{\circ}$C *during flowering and fruit set may substantially reduce berry number and ultimately yield. The impact appears to arise through both direct effects on reproductive development and indirect effects mediated through reduced assimilate availability and altered partitioning of resources.*

3.8.4 Development During the Vegetative Phase

The period between fruit set and veraison is critical because it largely determines final berry size (Considine and Knox, 1981). Consequently, this stage is deliberately targeted in regulated deficit irrigation (RDI) and partial root-zone drying (PRD) programmes used in wine grape production to limit berry growth and concentrate fruit composition (Dry et al., 2001).

Figure 3.14b demonstrates that high temperature reduces final berry size even in the absence of water-deficit stress (see also Greer and Weedon, 2014b). Water deficit and elevated temperature therefore act in the same direction by limiting berry development and reducing fruit quality. In commercial table grape production, where berry size is a major determinant of value, these stresses should be minimised during the period from flowering to veraison in order to maximise both fruit set and berry growth.

3.8.5 Ripening

Development and Injury

The effects of elevated temperature on berry development have recently been reviewed by Gouot-Davoust et al. (2026), who distinguished between sub-lethal injury occurring at approximately $35\,^{\circ}$C to $40\,^{\circ}$C and lethal injury at temperatures exceeding $40\,^{\circ}$C. Direct exposure of berries to temperatures of approximately $53\,^{\circ}$C to $55\,^{\circ}$C has been shown to be lethal in 'Shiraz' (Gouot et al., 2019b).

High temperature may also alter assimilate partitioning. Following a heat-stress event, translocation of recently fixed carbon to 'Chardonnay' berries was reduced to approximately 2.5% of that observed in control vines, with a much larger proportion directed towards actively growing shoot tips (Sepulveda et al., 1986; Sepulveda and Kliewer, 1986). Such responses demonstrate that heat stress can impair berry development indirectly through altered allocation of assimilates in addition to any direct damage to berry tissues.

Sub-lethal injury is most commonly expressed as sunburn, resulting from the combined effects of excessive temperature and high irradiance (Gambetta et al., 2021b; Müller et al., 2023). Symptoms are generally more apparent in white cultivars but may also occur in red and black cultivars, where loss of colour and uneven pigmentation are common consequences (Gambetta

Table 3.2: Approximate climatic thresholds beyond which productivity may be reduced and active management may be required. Values are indicative and vary according to cultivar, acclimation, water status and duration of exposure.

Process	Indicative threshold	Sensitive period
Assimilation		
Gas exchange	VPD $>$ 1.8 kPa	Bud burst to leaf fall
Photosynthesis	Air temperature $>$ 35 °C	Bud burst to leaf fall
Heat injury	Air temperature $>$ 40 °C	Bud burst to leaf fall
Photoinhibition	PAR $>$ 1500 μmol m^{-2} s^{-1}	Bud burst to leaf fall
Respiration		
Night temperature	$>$ 20 °C	Bud burst to leaf fall
Soil temperature (200 mm)	$>$ 20 °C	Bud burst to leaf fall
Inflorescence Initiation and Development		
Initiation	Optimum 20 °C to 32 °C	Approximately EL12 onward; each node enters a sensitive period 2–3 days after formation
Development	Optimum 20 °C to 32 °C	Approximately 90 days following initiation
Inflorescence ramification	$<$ 25 °C preferred	Bud burst to EL4
Fruit Development		
Flowering and fruit set	$<$ 30 °C	Cap fall $\pm$ 14 days
Berry growth	$<$ 30 °C	Cap fall to veraison
Ripening	$<$ 35 °C	Veraison to harvest

et al., 2021b). The synthesis of stress-related secondary metabolites may provide some protection against heat and radiation damage, although this protection is incomplete under severe conditions (Gambetta et al., 2021a).

Further evidence of heat damage was provided by Bonada et al. (2013), who increased field temperatures by approximately 2 °C to 4 °C above ambient. Under conditions where air temperatures periodically exceeded 35 °C before veraison and 40 °C after veraison, increased mesocarp cell death was observed in both 'Shiraz' and 'Chardonnay'. In 'Shiraz', these effects were also associated with berry shrivel and reduced fruit quality.

Composition

The influence of temperature extends beyond berry growth and survival to fruit composition. High temperature has long been associated with reduced colour development in red fruits (Mazza and Miniati, 1993), including grape berries (Kliewer, 1977; Mori et al., 2007; Sadras and Moran, 2012). Elevated temperatures affect not only pigmentation but also aroma and flavour development, although these attributes are generally of greater commercial importance in wine grapes than in table grapes (Gouot et al., 2019a).

Conclusion

Elevated temperature affects every stage of reproductive development, from inflorescence initiation and flower development through fruit set, berry growth, ripening and composition. Even short periods of heat stress may impair reproductive success and fruit quality. Consequently, management strategies that improve avoidance of, or adaptation to, high temperature are likely to be critical for successful table grape production in tropical, subtropical and other hot-climate regions.

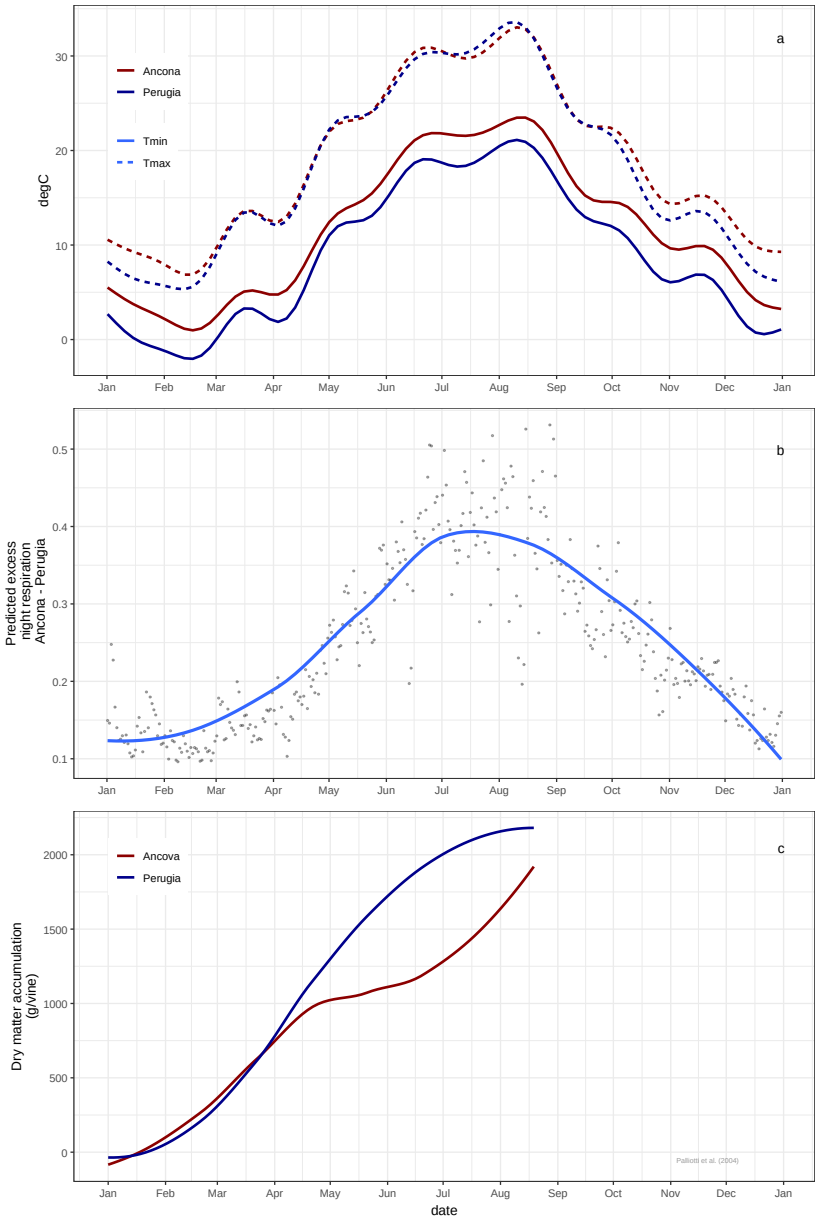


Figure 3.6: Figure illustrating the impact of even small differences in night temperature on respiratory losses. a, Tmin and Tmax for an inland site in Italy, Perugia and a coastal site, Ancona, 10 km from coast. The annual difference is $\approx 3^{\circ}$C. b, the difference in vine respiration calculated at Tmin using the data from Greer (2017). c, The difference in vine dry mass between the two sites over the course course of a season (Palliotti et al., 2004). All data is for 2003. Weather data obtained from ECMWF (2026)

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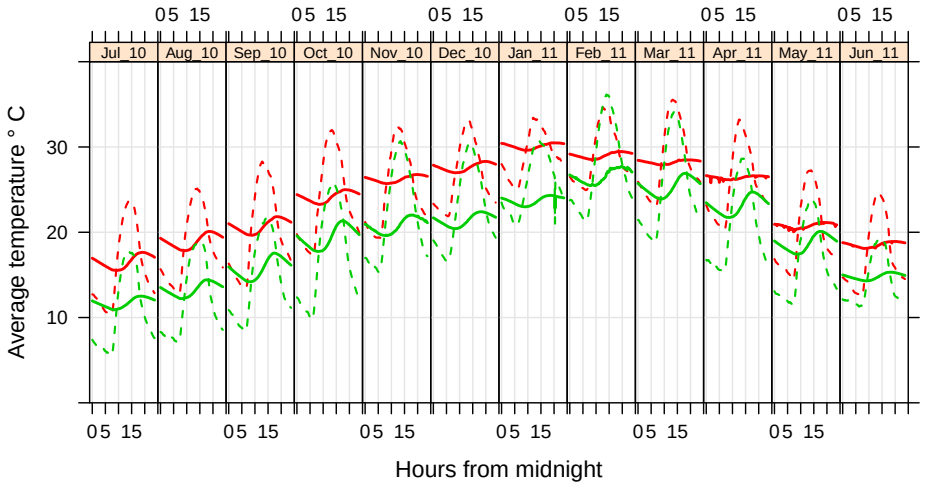


Figure 3.7: Air and soil temperature observations from vineyards in Carnarvon and the Swan Valley made during the 2010-11 season. Soil temperature obtained at 200 mm depth. The red lines represent represent the Carnarvon site and the green, the Swan Valley. The dashed lines, air temperature and the solid, soil. Source Considine and Considine, unpublished.

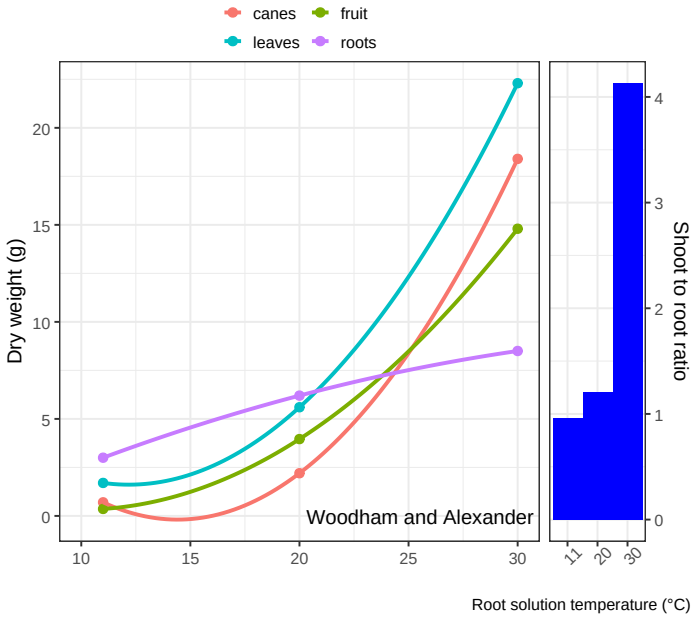


Figure 3.8: The impact of root temperature of one year old cv. Sultana, aerial layered cuttings, on growth, partitioning and shoot to root ratio. The cuttings were grown in hydroponics in a glasshouse (20 °C to 35 °C) (Woodham and Alexander, 1968).

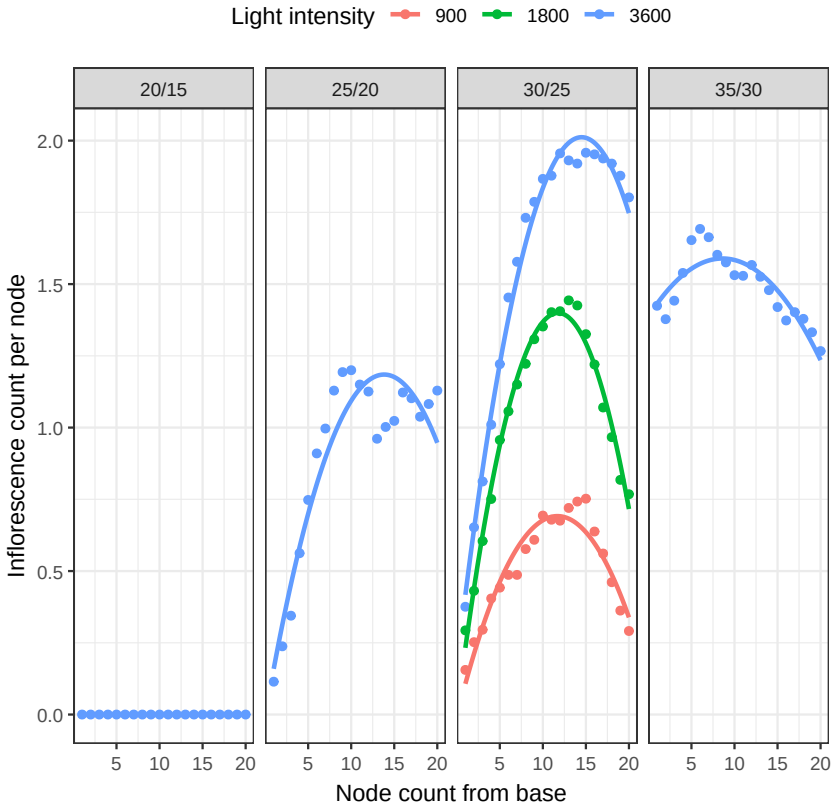


Figure 3.9: Impact of temperature and light intensity on inflorescence development under controlled environment conditions (Buttrose, 1969).

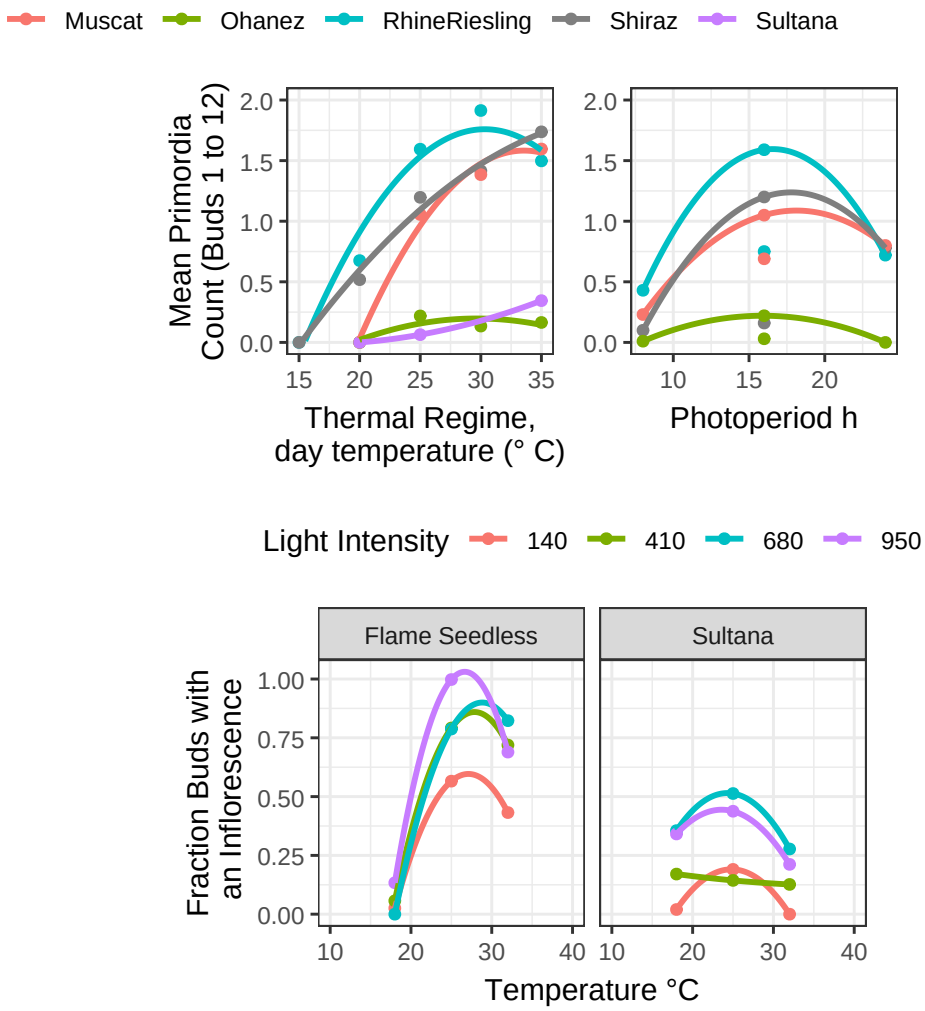


Figure 3.10: Impact of temperature, photoperiod and light intensity on inflorescence development under controlled environment conditions (Buttrose, 1969, 1970; Sanchez and Dokoozlian, 2005).

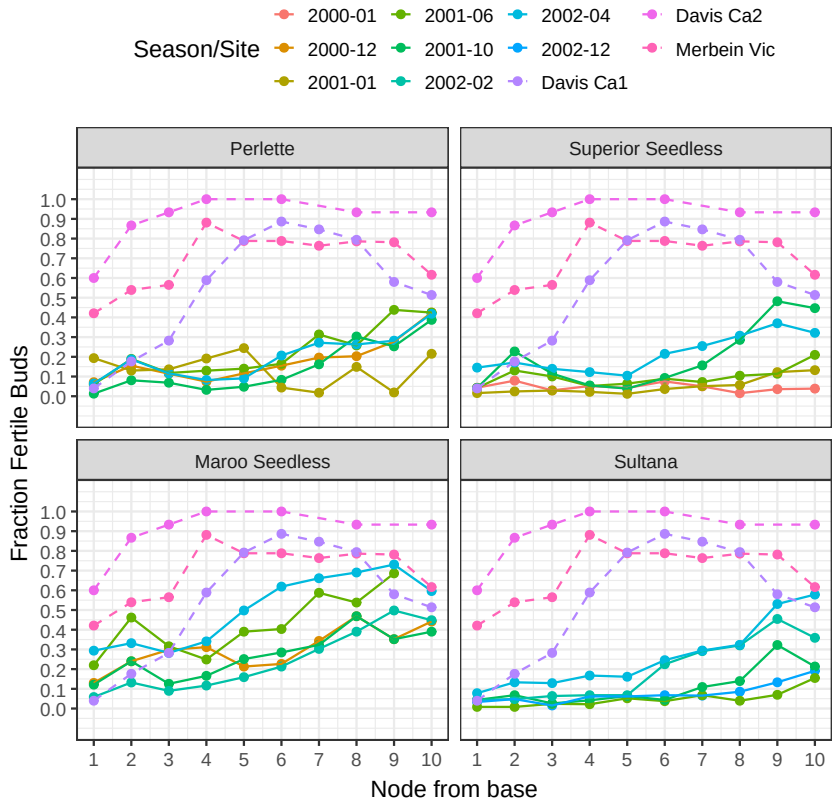


Figure 3.11: Historical data for bud fruitfulness in Petrolina, Brazil, compared with Davis, California, and Merbein, Victoria (Antcliff and Webster, 1955; Christensen, 1986; Leão and Da Silva, 2003b; Winkler and Shemsettin, 1937).

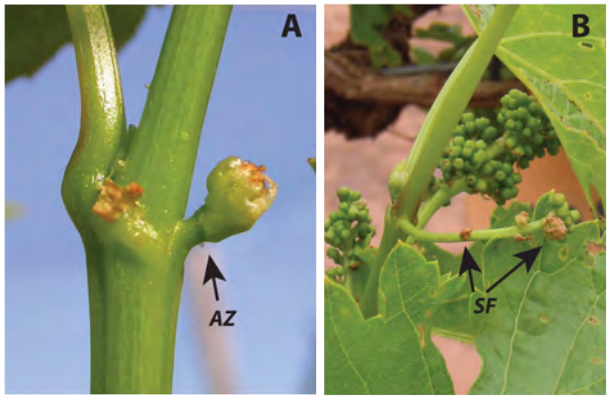


Figure 3.12: Examples of aborting and severely deformed inflorescences observed on vines growing in the Carnarvon region. "AZ" indicates the abscission zone. "SF" indicates bracts and aborting florets associated with a second-order inflorescence. Photo: JA Considine.

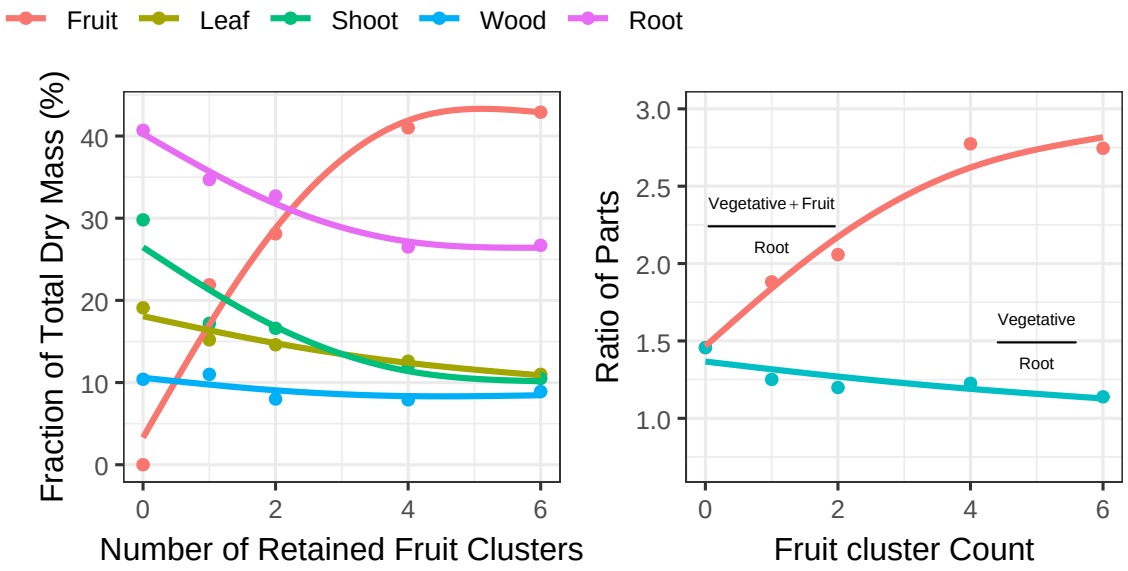


Figure 3.13: Impact of fruit load on the distribution of assimilates between organs and on the relative growth of the top *c.f.* the root system. Data from Howell (Table 5 2001) originally from Edson et al. (1995).

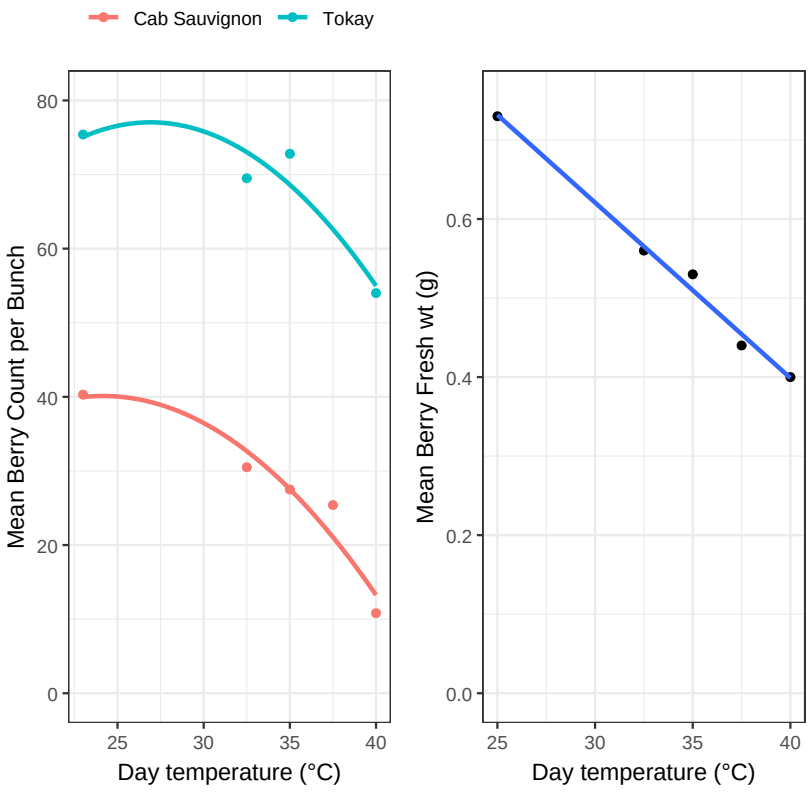


Figure 3.14: Effect of temperature during the flowering to fruit-set period on fruit set and berry growth. Data from Table 1 and interpolation of Figure 2A of Kliewer (1977).

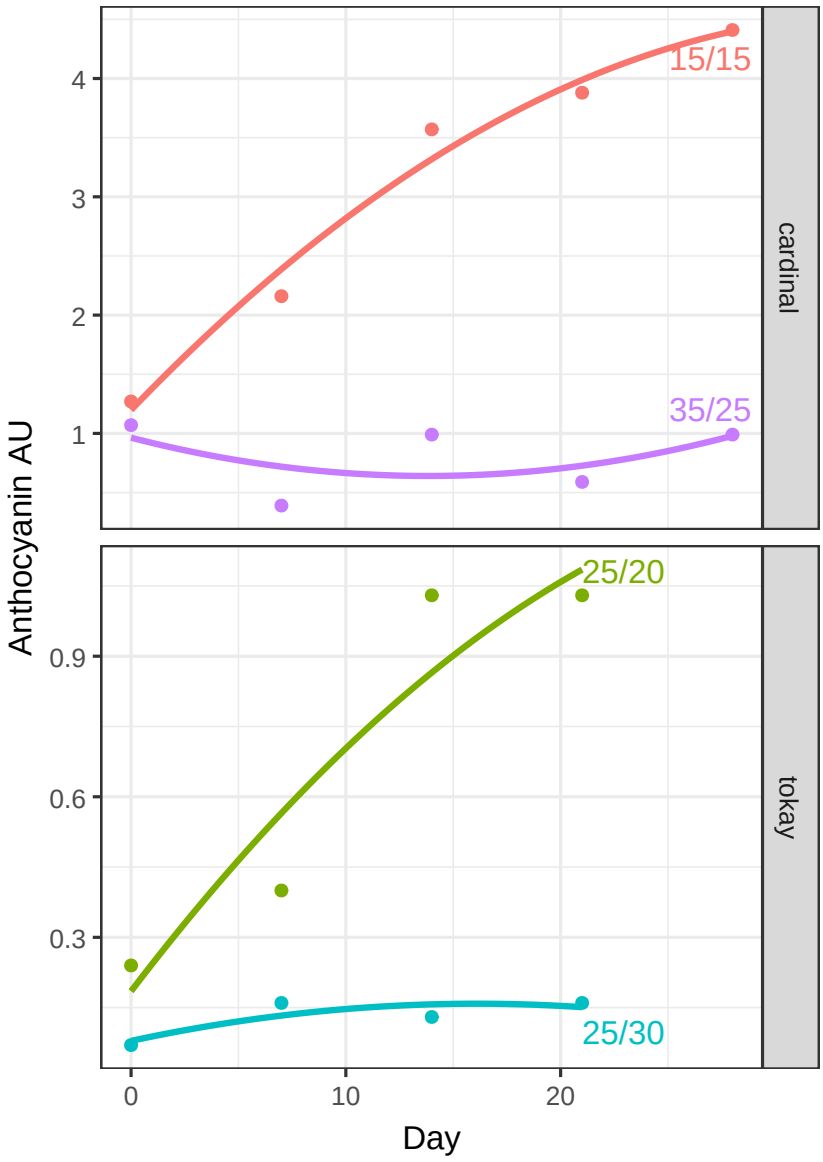


Figure 3.15: Impact of day–night temperature regimes on colour development in two grape cultivars. Curve labels indicate the day/night temperature treatment (°C). Redrawn from Kliewer and Torres (1972).

Chapter 4

Adaptive Management for Vines in Northern Regions of Australia

4.1 Introduction

Table grape production has a long history in tropical and subtropical regions worldwide, where growers have developed management systems that enable profitable production under conditions very different from those encountered in traditional temperate viticultural regions. Northern Australia shares many of the opportunities and constraints that have shaped these industries, including rapid vine growth, high temperatures, variable rainfall patterns, limited winter dormancy and the potential for multiple production cycles each year. As a consequence, production systems developed for temperate regions cannot be adopted without modification.

This chapter reviews management practices that may improve productivity under northern Australian conditions. Particular emphasis is placed on crop-cycle timing, reserve accumulation and remobilisation, assimilate partitioning, canopy management and the mitigation of heat stress. Experience from tropical viticultural regions, especially Brazil, demonstrates that these processes can be manipulated successfully through pruning strategy, irrigation management, plant growth regulators and other agronomic interventions.

The review also highlights opportunities for innovation. Field evaporative cooling, improved vineyard floor management, companion cropping and the adoption of adapted genetic resources may provide substantial gains in productivity, sustainability and fruit quality. Collectively, these approaches suggest that the principal challenge for tropical viticulture is not simply maintaining vine growth, but directing growth and resource allocation in ways that favour consistent flowering, fruitfulness and reserve renewal across successive production cycles.

4.2 Cycle Timing

Experience from the dry tropics of Brazil demonstrates the importance of avoiding rainfall during the post-veraison period, even for relatively disease-tolerant hybrid cultivars used in the grape juice industry and hardy *Vitis vinifera* cultivars grown for tropical wine production (Camargo, 2007; Pommer, 2006). The use of two productive cycles per year can produce annual yields approaching those achieved in traditional grape-growing regions (Marialava; compare Carnarvon and Petrolina, respectively Ahmed et al., 2019; de Azevedo et al., 2020). Double pruning was also introduced into the Jordan Valley during the early 1950s with the aim of obtaining a second harvest in early winter (Stoler, 1954a,b).

Prediction of grapevine phenology remains imperfect. Standard growing degree day (GDD) models were developed primarily for temperate viticultural regions (e.g. Gladstones, 1992; Huglin and Schneider, 1998; Winkler, 1963). However their application to tropical and subtropical regions is probalemmatic due to the non-linear response of grapevine development to temperature (Cameron et al., 2022; Merrill et al., 2020; Sadras and Moran, 2013). In this analysis, a tropical viticulture model using a base temperature of 12 °C was selected in preference to the traditional 10 °C threshold (Leão and Da Silva, 2003a). Phenological observations reported by Piña and Bautista (2004) are broadly consistent with this approach, although they are based on calendar time rather than accumulated thermal units. Evidence that night temperatures may have only a limited influence on phenological development (Fu et al., 2016) suggests that GDD-based estimates may not accurately represent grapevine development in subtropical and tropical regions. Consequently, cycle durations predicted for cooler sites may be underestimated. The objective of this analysis is illustrative rather than predictive. The cultivar Sultana was selected as a representative short-season cultivar. The results should therefore be regarded as exploratory and require experimental validation before practical application.

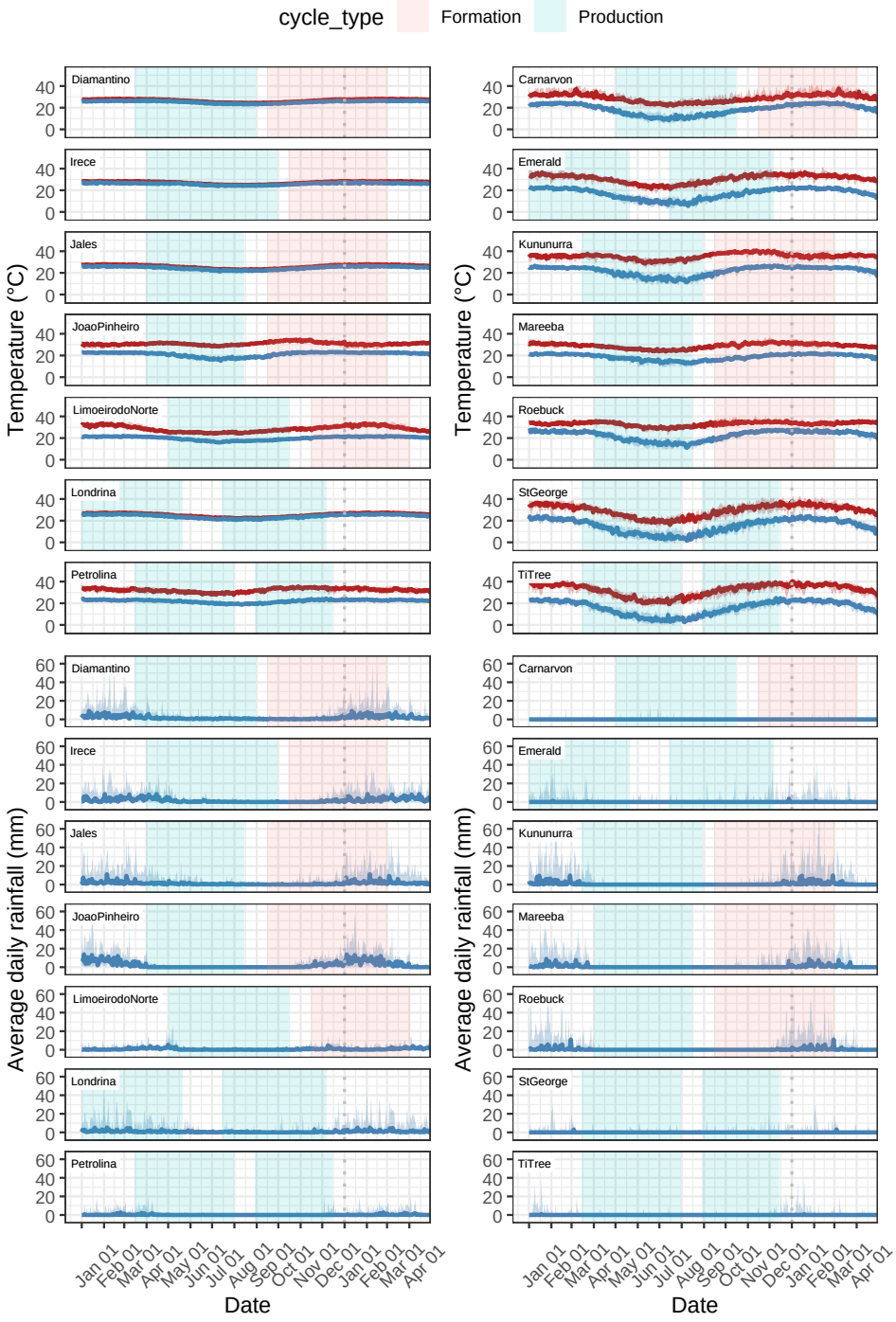


Figure 4.1: Comparison of production strategies reported for several Brazilian grape-growing regions (Camargo, 2007) with proposed strategies for climatically similar regions of northern Australia. The pink shaded areas represent the '(crop) formation' cycle and the blue, the 'cropping cycle'.

Figure 4.1 compares the production cycles described by Camargo (2007) for a number of Brazilian regions with those proposed for climatically similar regions in northern Australia (see Figure 2.6 and associated figures and tables). Rainfall distribution and thermal regimes are shown for context. Londrina is broadly comparable in latitude to Emerald ($-23.2°$ versus $-23.5°$) and Carnarvon ($-24.8°$). In most regions, production follows a single harvest cycle preceded by a formation cycle that coincides with the rainy season. Exceptions include Petrolina, where arid conditions minimise rainfall risk, and Londrina, where production is based largely on hybrid cultivars for juice and table grape markets. Although located near the Tropic of Capricorn, Londrina experiences a relatively equable subtropical climate compared with the true tropical conditions of Diamantino ($-14.2°$), Irecê ($-11.2°$), and Jales ($-20.2°$). These milder conditions may favour longer periods of leaf retention

and sustained canopy function.

In general, northern Australian production regions experience cooler night temperatures than comparable Brazilian sites. The impact of this on the length of the production cycle according to pruning date for 'Sultana' is shown in Figure 4.2. This may favour productivity through reduced respiratory losses, increased carbon-use efficiency, and improved cane maturation. The Australian production schedules shown in Figure 4.1 were derived from estimates of the interval between pruning and harvest under average climatic conditions (Figure 4.3). Figure 4.3 illustrates the relationship between pruning date and predicted harvest date for Sultana at a site climatically comparable to Roebuck. The lower panel shows the predicted harvest date corresponding to each pruning date, while the upper panel indicates mean rainfall during the veraison-to-harvest period. Table 4.4 identifies pruning periods associated with a low risk of rainfall during harvest across northern Australian production regions. These estimates represent an idealised scenario and do not account for additional constraints, such as the "sick" period identified by Ian Cameron (DPIRD), during which shoot development following budburst may be abnormal[1].

Figure 4.2 highlights the influence of climate on production-cycle duration. Based on the criteria applied here, only Roebuck and Kununurra appear likely to support multiple annual production cycles, although Mareeba may also be suitable. Emerald, St George, and Ti Tree appear climatically suitable from a thermal perspective, but winter chilling may limit the viability of a second crop. For the remaining sites, production-cycle duration is likely to preclude the approach evaluated here, although alternative management strategies may still be feasible (Bernstein and Klein, 1957; Camargo, 2007). More comprehensive models incorporating climate, phenology, reserve accumulation, and economic considerations may assist in identifying optimal production systems. Carnarvon presents an interesting case. Its arid climate appears suitable for a cycle commencing in early May and harvested in early to mid-November, followed by a second pruning in late December. Although attractive in theory, local experience suggests that physiological disorders may prevent such an early pruning (I. Cameron, DPIRD, pers. comm.). A production system more closely aligned with that used in Londrina may therefore prove more suitable (Camargo, 2007).

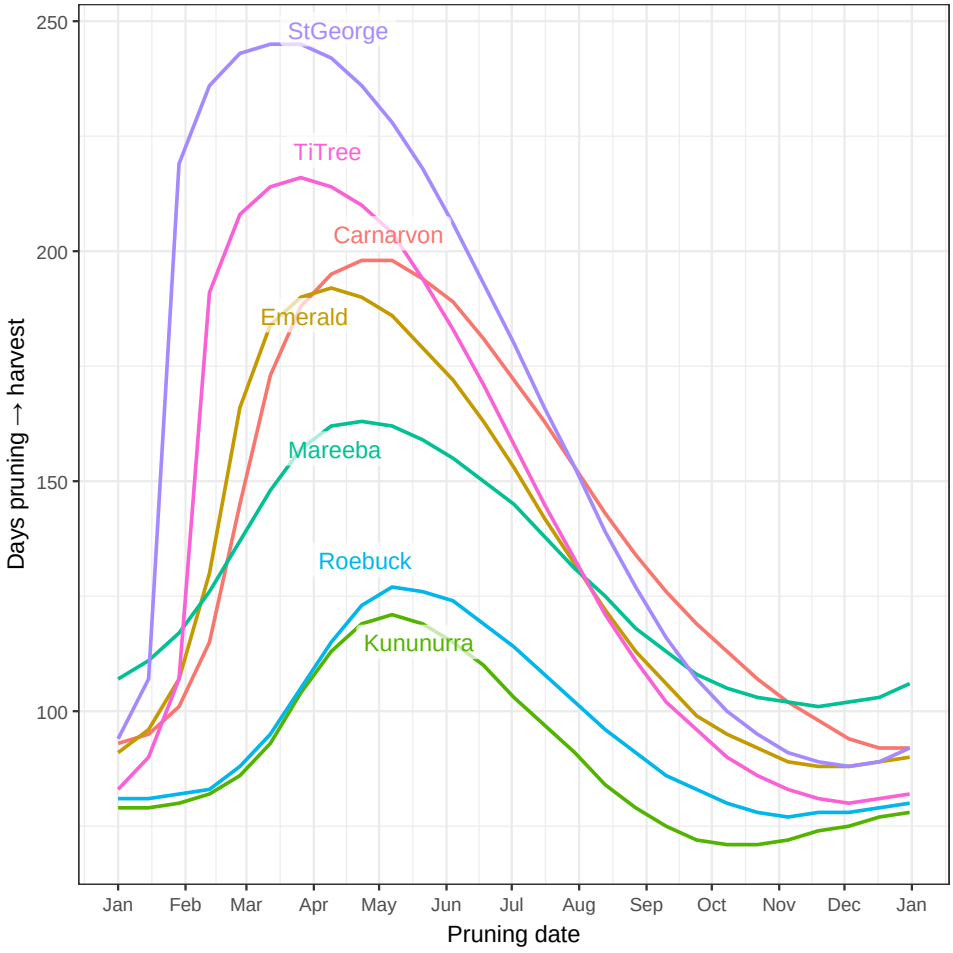


Figure 4.2: Effect of location on the period from pruning to harvest in northern Australian table grape production regions for cv. Sultana, based on thermal requirements reported for Petrolina, Brazil (Leão and Da Silva, 2003a).

[1]Symptoms are chlorosis, arrested growth and erratic bud burst.

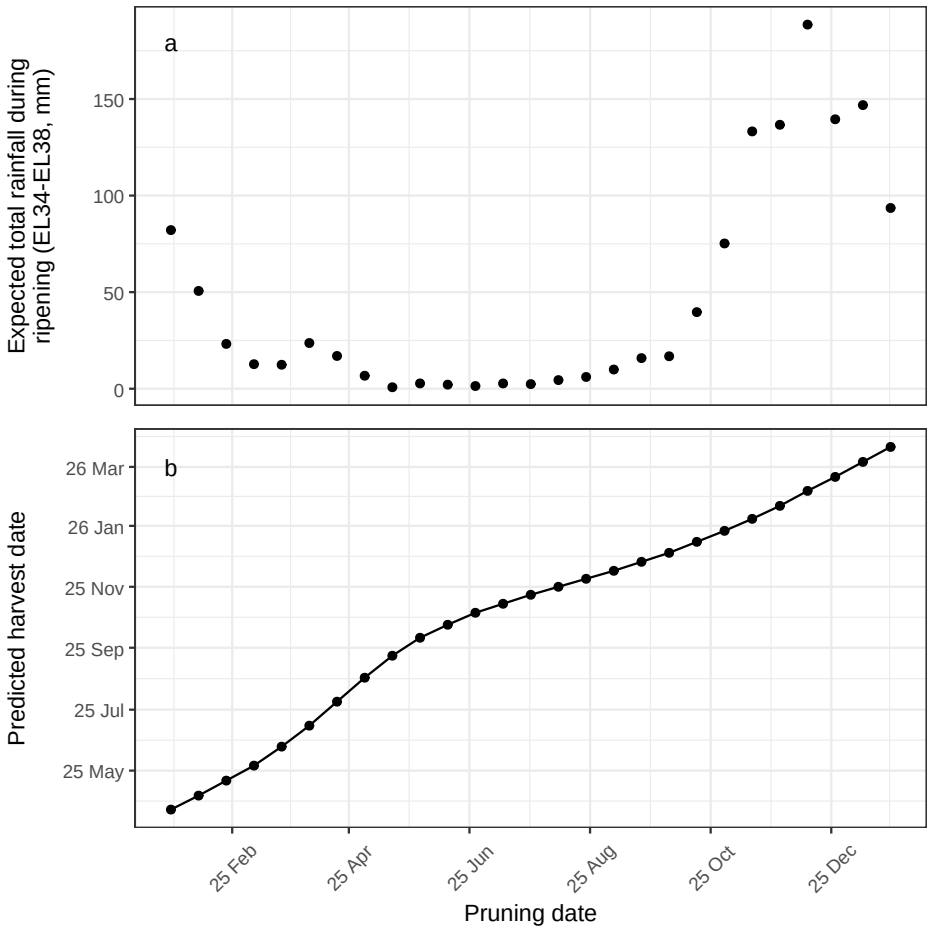


Figure 4.3: (a) Predicted harvest date as a function of pruning date for a Roebuck-type environment, based on the thermal requirements of cv. Sultana (base 12 °C) reported for Petrolina (Leão and Da Silva, 2003a). (b) Mean rainfall during the veraison-to-harvest period based on a 26-year climatic average (Projections and Team, 2024).

Keys to Successful Multi-Cycle Production

1. Schedule pruning so that harvest occurs during a dry period while also considering market supply and demand.
2. Where a formation cycle is used, time the second pruning to ensure adequate carbohydrate reserves remain available for canopy development and the subsequent production cycle (Hall et al., 2016).
3. For production cycles, evaluate rainfall patterns and disease risk before selecting pruning dates.
4. Determine whether the annual photoperiod range is sufficiently small to avoid growth cessation or dormancy.
5. Determine whether minimum winter temperatures are high enough to sustain growth and minimise leaf loss.
6. Determine whether mean temperatures are sufficient to support a short production cycle.

4.2.1 Transition Between Cycles: Shutdown

A critical, but poorly understood, step in multi-cycle viticulture is the transition between harvest and renewed growth. Following the completion of one production cycle, reserves stored in roots, trunks, and permanent cordons must be mobilised to support budburst and early shoot growth in the next cycle. Copious xylem bleeding from freshly pruned vines indicates that reserve mobilisation is active and that 'root' pressure has been restored. This pressure develops because sugars are 'pumped' into the xylem raising its osmotic pressure. In temperate viticulture this transition is associated with winter acclimation. Exposure to chilling promotes cane maturation and induces physiological changes that subsequently enable vines to respond to accumulated heat units. The processes of cold acclimation have been studied extensively because of their importance for freezing tolerance in high-latitude continental regions (reviewed by Guo et al., 2025). By comparison, the de–acclimation process remains less well understood.

De–acclimation is associated with reserve mobilisation, accumulation of sugars and amino acids in the xylem stream, and ultimately budburst (Figure 3.1). In tropical regions, where chilling is limited or absent, this phase must instead be induced

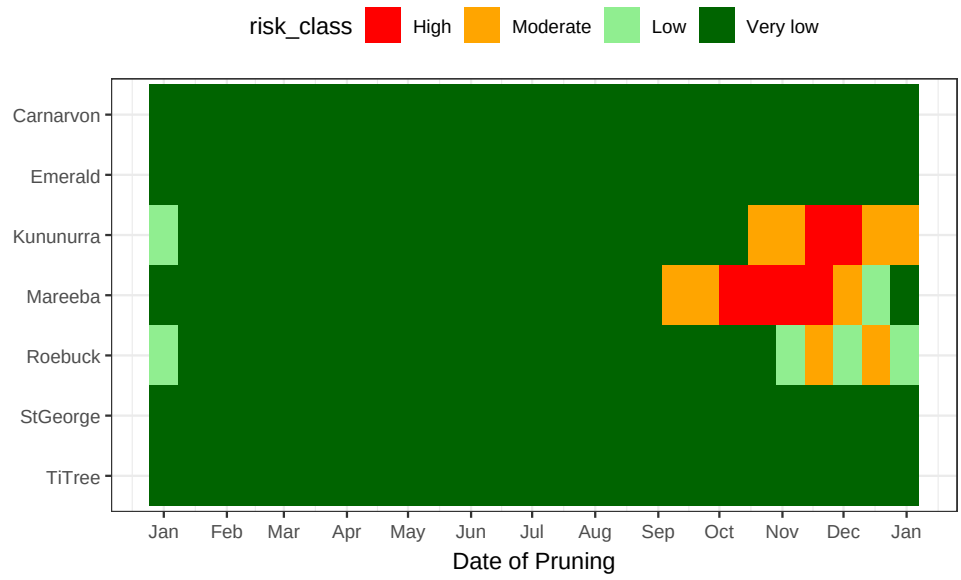


Figure 4.4: Heat map showing the predicted risk of rainfall at harvest for cv. Sultana across Australian production regions and pruning dates.

through vineyard management. Some elements of the spring mobilisation process may occur continuously on a smaller scale under warm-climate conditions (Tixier et al., 2018). Auxins released from actively growing shoots may stimulate the mobilisation of local starch and nitrogen reserves and, where phloem transport remains functional, may influence reserve utilisation elsewhere in the vine (Aloni et al., 1991; Esau, 1948). In contrast, temperate vines emerging from winter acclimation rely heavily on xylem transport because phloem function ceases in the acclimatised state and is not renewed until after bud burst (Esau, 1948).

Water-deficit stress is commonly used to initiate shutdown and transition into the next cycle. However, recommendations are generally empirical and not tailored to specific environments. Typical guidelines involve progressive reductions in irrigation, for example by one-third followed by a further halving of water supply (Camargo, 2007). Such recommendations may conflict with the final stages of reserve accumulation, which depend on continued photosynthesis after harvest and during cane maturation (May et al., 1969; Zapata et al., 2004). This is particularly relevant where irrigation restrictions commence up to three weeks before harvest (Camargo, 2007).

Towards the end of the stress period, ethephon is commonly applied to promote cane maturation and leaf abscission (Bondada and Shutthanandan, 2012; Shulman, 1982; Shulman et al., 1980). Interestingly, many physiological responses associated with winter acclimation overlap with those induced by drought stress. Adaptation to freezing stress frequently confers increased drought tolerance (e.g. Blödner et al., 2005; Neto-Bradley et al., 2026).

In grapevines, winter acclimation is associated with dehydration of aerial tissues, partial conversion of starch reserves to soluble sugars, callose deposition and complete phloem occlusion, and the accumulation of arabinogalactan-rich gums within the xylem (Guo et al., 2025; Price et al., 2015; Sun et al., 2008; Xie et al., 2018). It is therefore plausible that carefully managed water-deficit stress initiates at least part of the same physiological sequence under tropical conditions. The effectiveness of reserve mobilisation may be assessed indirectly through xylem bleeding following pruning. Both the volume of bleeding sap and its sugar concentration have been proposed as indicators of reserve remobilisation (e.g. Roubelakis-Angelakis and Kliewer, 1979; Zapata et al., 2004). A simple hand-held refractometer may therefore provide a practical method for assessing the strength of the recycling process and the readiness of vines to commence a new growth cycle.

Managing water-deficit stress remains challenging because practical decision thresholds are poorly defined. Partial root-zone drying may have a role, although its primary purpose is generally to minimise whole-plant water stress through hydraulic redistribution from wetter portions of the root system while signalling stress to slow growth (Neumann and Cardon, 2012). A range of monitoring tools is available, including visual symptom assessment (Hardie and Martin, 2000), soil-moisture sensors, tensiometers, sap-flow systems, trunk-diameter gauges, pressure chambers, and lysimeters. However, interpretation can be difficult and formal guidelines are lacking. Measurements of sugars in buds and canes may provide quantitative indicators of cane maturation (Kita et al., 2024), while hand-held chlorophyll meters may offer a practical means of monitoring the progression of shutdown and senescence in the vineyard (Bresson et al., 2018).

A further consideration is the importance of normal leaf senescence. Autumn senescence enables the recovery and redistribution of nitrogen and mineral nutrients from leaves to perennial storage tissues, making an important contribution to the

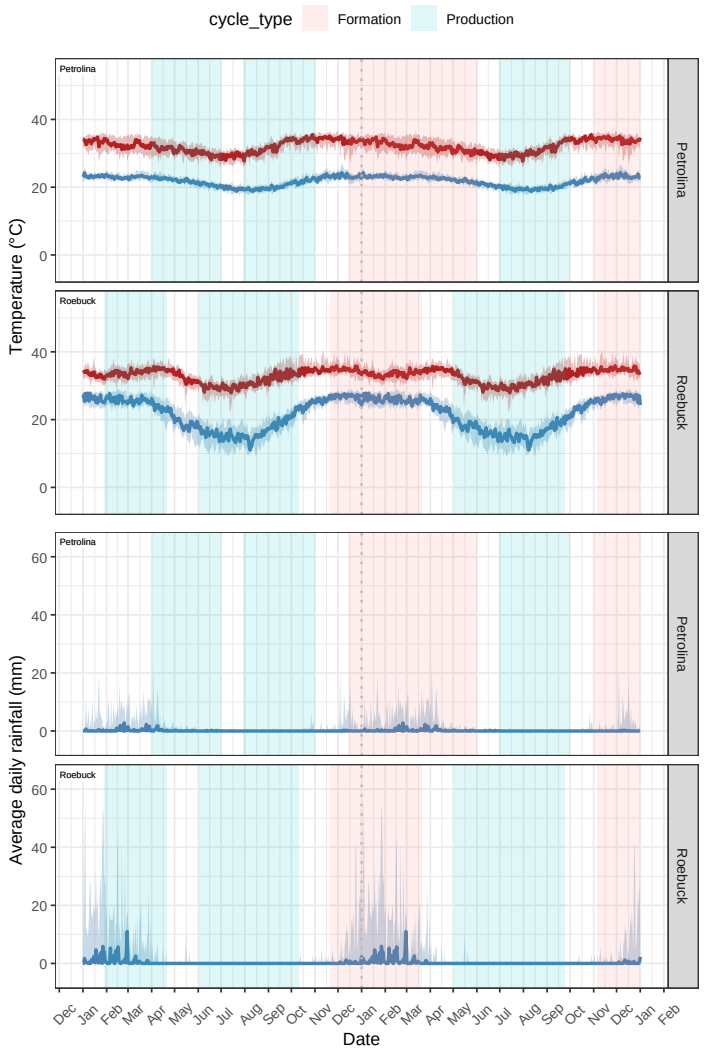


Figure 4.5: Comparison of a multi-cycle production system in Petrolina (Camargo, 2007) with a proposed multi-cycle system for Roebuck based on phenological data for cv. Sultana in Petrolina (Leão and Da Silva, 2003a). The pink shaded areas represent the '(crop) formation' cycle and the blue, the 'cropping cycle'

nutritional requirements of the subsequent growth cycle. This process is highly regulated and involves substantial nutrient remobilisation (Bresson et al., 2018). Consequently, rapid desiccation of leaves is unlikely to be desirable. Higher rates of ethephon than those required to suppress shoot extension can initiate leaf senescence and abscission in mature grapevine leaves while maintaining a more natural senescence pathway (Hendgen et al., 2021; Hirschfeld and Lavee, 1980; Mannini et al., 1983). Ethephon has also been reported to promote cane maturation (Bondada and Shutthanandan, 2012).

Thus, the key objective of shutdown management is to ensure that water-deficit treatments initiate a durable stress-adaptation response while promoting cane maturation, leaf senescence, and subsequent abscission. In effect, the process seeks to recreate the physiological transition that occurs naturally during autumn and winter in temperate climates, thereby preparing the vine for efficient reserve mobilisation and the initiation of the next growth cycle.

Studies undertaken as part of the present investigation indicate that reserves stored in the roots, and to a lesser extent in the permanent aerial structure, are not remobilised to any practically significant extent. This suggests that current shutdown practices are not consistently inducing the physiological changes required for reserve recycling. Consequently, the shutdown process and the methods used to initiate it require re-evaluation.

4.3 Managing Partitioning of Assimilates

Figure 4.6 illustrates the principal pathways that assimilates may follow after their production in leaves. Photoassimilates are allocated among competing sinks, with partitioning largely determined by sink strength. In general, the faster the growth

rate of a tissue, the greater its capacity to attract resources. Consequently, developing inflorescences are at a competitive disadvantage compared with rapidly growing shoots, despite their importance to yield. Where carbohydrate supply is limited, reproductive development may be compromised in favour of vegetative growth. This relationship changes sharply at veraison.

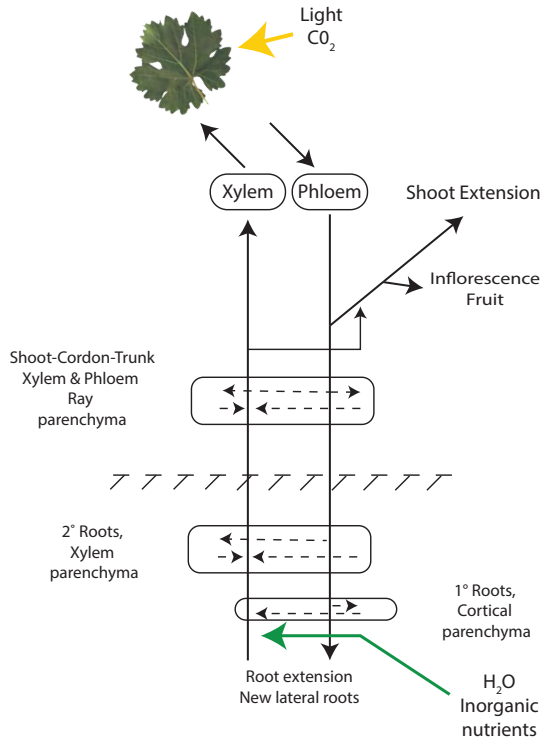


Figure 4.6: Diagram of the paths photoassimilates may take in circulating from leaf to tissue or to reserve and return.

Once ripening begins, few tissues can compete with the berry. The strong sink strength of the ripening fruit arises from the active transfer of sugars from the phloem into the berry pericarp, effectively creating a metabolic pump that drives continued accumulation of sugars within the fruit (Ren et al., 2020).

It is not widely appreciated that stored carbohydrates and nitrogen reserves are mobilised to developing shoots primarily via the xylem during budburst and the early stages of shoot growth (Sauter et al., 1973). Xylem transport may also contribute to maintenance of vegetative tissues during the night (Tixier et al., 2018). Consequently, there is a dynamic exchange between reserve tissues and developing shoots during the early growth phase. Functional phloem connections are not fully re-established until several weeks after budburst (Esau, 1948).

In temperate regions, shortening day length and declining temperatures progressively reduce vegetative growth during autumn. As shoot growth slows, reserve tissues become increasingly competitive for assimilates. Unlike shoots, reserve tissues do not compete through growth but through the conversion of soluble sugars into stored carbohydrates, principally starch. This seasonal reduction in shoot growth creates the conditions necessary for replenishment of root and stem reserves. Such a growth slowdown is largely absent in equable tropical environments and occurs only weakly in seasonal tropical and marginal subtropical regions.

Roots are capable of growth throughout the year, provided soil temperature, soil moisture, and carbohydrate supply remain adequate. Although a natural balance between root and shoot growth is maintained through hormonal signalling (Richards and Rowe, 1977a,b), roots are generally weaker sinks than actively growing shoots because they occupy a downstream position within the assimilate pathway. The maintenance of root-shoot balance has been shown to operate on a daily basis in grapevines and responds to both photoperiod and temperature (Mahmud et al., 2018). The tropical viticulturist must therefore create alternative mechanisms to mimic the effects of autumnal growth cessation.

The importance of this process is highlighted by observations from the present study indicating that reserve mobilisation between cycles is often poor. If reserves are not replenished effectively prior to shutdown, or cannot be efficiently recycled during the subsequent growth cycle, vine vigour and productivity will be substantially reduced. Managing assimilate partitioning is therefore central to the success of multi-cycle production systems.

4.3.1 Pruning and Vine Architecture

Canopy structure has important implications for vine performance, productivity, and fruit quality. Trellis and training systems are currently being re-evaluated across viticultural industries worldwide as growers seek to adapt to warmer climates and an increased frequency of extreme heat events (Millan et al., 2025; Reta et al., 2025). These considerations have long been important in tropical fruit production and remain highly relevant to viticulture in northern Australia. Pruning severity, trellis design, and rootstock selection all influence realised bud fertility, yield, and vine balance. As in other production regions, achieving an appropriate balance between vegetative growth and cropping remains a primary objective, often described as "pruning to vigour" (Sommer et al., 2000, 2001).

A comprehensive review of grapevine training and trellising systems has been provided by Carbonneau and Carnello (2003), while Smart (1988) reviewed many of the principles underlying trellis design from the perspective of light interception and canopy function. Table grape vineyards are commonly cane-pruned because many traditional table grape cultivars exhibit relatively poor fertility in basal buds. Bud fertility may be further reduced under tropical conditions (Leão and Da Silva, 2003b). Consequently, production is typically based on fruiting canes, while formation cycles rely principally on spur growth. Where two consecutive production cycles are planned, a mixed system of replacement spurs and productive canes is often employed. Unlike traditional cane-pruning systems, however, the principal cane developed during the formation cycle is tipped to encourage the growth of several basal axillary shoots. These shoots subsequently become the foundation of the following production cycle (Camargo, 2005). Successful implementation of this approach depends on the development of sufficient vine vigour during the formation phase.

Apical dominance is generally strong under tropical conditions and intervention is commonly required to achieve uniform budburst. Hydrogen cyanamide remains the most widely used dominance-breaking agent, although alternative formulations have also been reported. These include products suitable for certified organic production, such as sulphocalcic syrup (5%) combined with mineral oil and an adjuvant (BASF Assist®, 2%) (Mariani et al., 2019). A particularly innovative approach, which may enable a form of double cropping in regions where conventional multi-cycle systems are constrained, involves dividing the production potential of a shoot into two sequential harvests. In this system, only the distal three or four buds are initially allowed to burst and develop. Their growth suppresses the basal buds through apical dominance. After harvest, the distal fruiting section of the shoot is removed, allowing the previously suppressed basal buds to burst and produce a second crop. This system has been used in the Londrina region of Brazil and demonstrates an alternative means of increasing cropping frequency where complete cycle duplication may not be feasible (*e.g.* Camargo, 2007). This is not dissimilar to the system developed in the Jordan Valley (Stoler, 1954a,b).

4.4 Trellis Design and Canopy Management

Three trellis systems are commonly used in the Australian table grape industry: the ‘Y’, ‘Link’, and a wide sloping ‘T’ trellis. Each is designed to position bunches beneath the canopy, improving accessibility while reducing the risk of mechanical damage during vineyard operations. A fourth system, the overhead pergola, is widely used in countries such as Brazil, Chile, Spain, and Italy. Nevertheless, vertical trellis systems remain common in many production regions because of their relatively low capital cost and the absence of a requirement for specialised low-profile machinery.

Beyond their effects on canopy architecture and fruit exposure, trellis systems influence the vineyard microclimate. Wider canopies generally provide greater shading of the vineyard floor, reducing reflected radiation, soil-surface temperatures, and evaporative losses. These effects are particularly important in hot production environments (see Vineyard Floor Management below). However, increased shading may reduce the productivity of companion crops or cover crops where these form part of the vineyard management system. Row orientation is also an important consideration. North–south row orientation is generally preferred because it distributes sunlight more evenly throughout the day and can reduce the risk of sunburn on fruit exposed on the northern side of the canopy. The importance of row orientation is reduced in divided-canopy systems such as the ‘Link’, ‘Y’, and pergola trellises, where canopy architecture moderates fruit exposure more effectively than in simpler vertical systems (*e.g.* Gambetta et al., 2021a; Zufferey and Murisier, 2003; Zufferey et al., 1998).

The combination of trellis design, canopy management, and row orientation ultimately determines the balance between light interception, fruit exposure, vineyard temperature, and water use. In northern Australian environments, where excessive heat is often a greater concern than insufficient sunlight, canopy systems that provide partial shading while maintaining adequate air movement may offer important advantages.

4.5 Irrigation

Irrigation is an essential component of table grape production and the strategies adopted vary somewhat from those common to the wine industry. Despite the scale and global economic importance of this sector, the special needs of this sector have rarely been the prime consideration in irrigation research, generally. Quality in the table grape industry revolves around berry size, texture, sugar acid balance, visual appeal and fruity aroma. High yields, as in the wine industry, are not usually a consideration, but constrained yields are. Crop management in table grape production frequently leads to excessive vegetative growth. Controlled deficit irrigation offers benefits in this respect along with improved berry colouration, earlier maturity, reduced primary bud necrosis and water savings from 20 to 80% depending on circumstances and policy (Conesa et al., 2022; Dry, 1997; Kang and Zhang, 2004; Sadras, 2009; Santos et al., 2003).

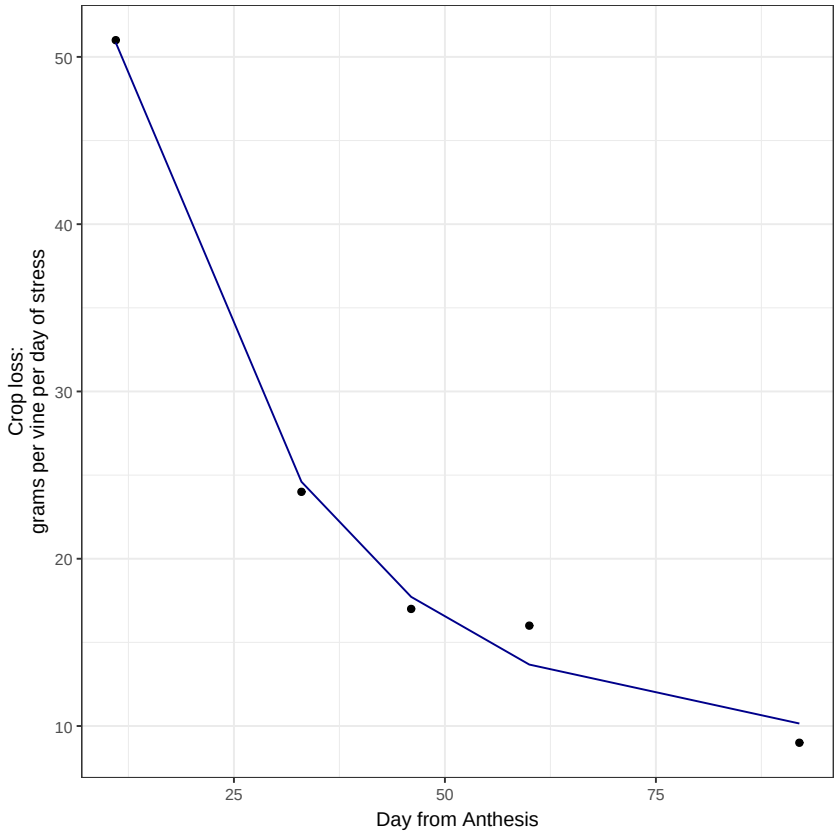


Figure 4.7: Relative sensitivity to water deficit stress plotted as yield loss for unit of stress from anthesis to maturity (Hardie and Considine, 1976).

Figure 4.7 shows a principle underlying the need for high water status during the flowering to harvest period: flower set is an extremely sensitive phase and that sensitivity declines sharply once the berry has set. Water deficits during the post-set to veraison phase can lead to smaller berries, an undesirable outcome for table grape production, but a focus for fine wine producers (Calderon-Orellana et al., 2014; Chaves et al., 2010). Sensitivity declines through the post set period due to the early cessation of pollination-induced cell division and as cell expansion reaches its zenith (Considine and Knox, 1979, 1981).

Thus all irrigation practices designed for table grapes should ensure fully hydrated vines during the flowering to fruit set period. This does not necessarily preclude partial root zone drying (PRD) as originally conceived, because leaf water status remains similar to that of fully irrigated vines (Dry, 1997; Stoll et al., 2000) and full irrigation can be detrimental (Dry, 1997).

The case for moderate irrigation is strengthened by the observations of Nir et al. (2000) who found that full irrigation under the hot, dry conditions of the Jordan Valley reduced yields through poor cane maturity, high levels of primary bud necrosis and delayed bud burst. Additionally, excessive irrigation, postharvest, has been implicated in a physiological disorder of 'Sultana' growing in the lower Orange river Basin, Namibia. This was judged the cause of substantial yield losses associated

with poor starch accumulation in roots, postharvest, xylem blockages and epidermal cell death (de La Harpe and Archer, 1981; Saayman, 1983a,b). Symptoms included restricted growth, bunch shedding and poor fruit set.

These observations are consistent with the hypothesis developed earlier in this chapter that successful multi-cycle production depends not only on current-season yield formation, but also on the accumulation and subsequent remobilisation of reserves between cycles.

A detailed study on the table grape 'Crimson Seedless' growing in southern Spain showed that, in practice, only severe water-deficit stress caused a reduction in berry quality (size) (Conesa et al., 2022). Each of the irrigation reduction programs assessed were applied and which were applied from fruit set to harvest gave better outcomes than full irrigation (110% crop evapo-transpiration, ET_c). An important consequence of adopting a controlled deficit irrigation practice is that of increased water use efficiency which has been reported to be in the order of 20 to 80%, depending on the strategy adopted . A further potential benefit in tropical and subtropical environments is the stimulation of stem maturity through the increase in xylem abscisic acid (ABA) and the reduction of cytokinins (however, note that cytokinins are important at bud burst for inflorescence development).

Experience has shown that the need for monitoring PRD is minimal while that for regulated deficit irrigation (RDI) is more demanding. RDI can be highly effective and its adoption avoids the need for the capital investment required by PRD (essentially, double the drip line and controller units) (Cifre et al., 2005; Sadras, 2009). A general approach to planning deficit irrigation has been published Lecler (1998) but it doesn't consider PRD. However, it is important that a reliable system of monitoring is established at the beginning and that it is recognised that individual cultivars may respond differently depending on their genetic background as being either an-isohydric, isohydric or somewhere in between (Chaves et al., 2010; Schultz, 1997).

PRD and similar strategies lead to enhanced root development, nutrient uptake, soil health, reduced shoot extension (*i.e.* leaf production is constrained as is lateral shoot development). Shoot thickness is reported as not being impacted (Dry, 1997; Stoll et al., 2000). This is important because there is a correlation between the size of the shoot and that of the bunch and subsequently, of the berries (Considine, unpublished data, (see also Eltom et al., 2014)). Furthermore, in the formation cycle, restraint of irrigation may need to be deferred if the strategy of encouraging development of the basal lateral shoots as primary units of production is adopted (Camargo, 2000).

4.6 Plant Growth Regulators

4.6.1 Growth Retardants

Plant growth regulators (PGRs) have been used to manage a range of physiological disorders that are common in tropical and subtropical table grape production. These include poor inflorescence development, inflorescence abscission following budburst, inadequate development of inflorescence primordia during the formation phase, excessive vegetative growth, and high levels of primary bud necrosis (PBN). Numerous studies have demonstrated that growth-retarding compounds can alleviate many of these problems while improving vine balance and productivity (e.g. Carreño et al., 2007; Christov et al., 1995; Collins and Rawnsley, 2008; Reynolds et al., 1992; Shaltout et al., 1988).

A range of commercial products is also marketed for use in table grapes, including seaweed extracts and SugarMover®. However, relatively few have been subjected to rigorous independent peer-reviewed assessment and they are therefore not considered further here. This should not be interpreted as evidence of ineffectiveness. Among the plant growth regulators most extensively studied in grapevines are the gibberellin biosynthesis inhibitors, chlormequat chloride (Cycocel®, CCC), paclobutrazol (Cultar® α–tert–β–(4-chlorobenzyl)–1H–1,2,4–triazole–1–ethanol), uniconazole, prohexadione, but also abscisic acid (ABA), ethephon (Ethrel®, 2–chloroethylphosphonic acid), and the ethylene precursor 1-aminocyclopropane-1-carboxylic acid (ACC; Accede®) (reviewed by Rademacher, 2000).

Plant Growth Retardants

Figure 4.8 illustrates some of the benefits associated with application of the gibberellin inhibitor paclobutrazol. Paclobutrazol is available under many trade names but most commonly as Cultar® (Similar to CCC, prohexadione and uniconazole, paclobutrazol acts by inhibiting gibberellin biosynthesis. The experiment compared soil application with application to the vine canopy. The response was broadly similar for both methods. However, yield responses tended to be greater following canopy application than soil treatment. Not all published reports have found positive responses to the application of paclobutrazol via the soil (Williams et al., 1989). Nevertheless, soil application remains the preferred approach in many perennial fruit crops. Improved optimisation to soil type may provide equivalent responses in grapevines, as has been demonstrated in other crops such as mango (*e.g.* Sharma and Awasthi, 2005; Wu et al., 2013).

Figure 4.8 illustrates both the carry-over effects of paclobutrazol and the consequences of repeated annual applications. Shoot extension declined approximately log-linearly with increasing application rate in every year of assessment (Figure 4.8a). Moderate application rates increased yield during the season of treatment (Figure 4.8c), although this benefit was not maintained

in the absence of retreatment. Repeated annual applications, however, resulted in an approximate doubling of yield. Similar responses have been reported by other authors over three successive production cycles (Wassel et al., 2023, 2024).

In these studies, paclobutrazol was generally applied once, either immediately before or at bud burst. Other researchers have reported benefits from later applications, including increased bud fruitfulness following treatment at fruit set (Carreño et al., 2007) and increased berry volume together with reduced lateral shoot growth following application when berries reached 3–5 mm diameter (Reynolds et al., 1992). In 'Superior Seedless', applications of 0.5 or 1.0 g/L improved yield, berry size, pruning weight and wood maturation (Wassel et al., 2023). Additional reported benefits include reduced primary bud necrosis and improved bud fruitfulness. These responses may arise partly through reduced competition from vegetative growth and partly through hormonal effects. Gibberellin-biosynthesis inhibitors such as paclobutrazol, uniconazole and CCC have been shown to increase cytokinin concentrations in xylem sap and improve bunch retention following bud burst (Bindra et al., 1975; Mullins, 1968; Skene, 1970; Srinivasan and Mullins, 1980).

CCC has also been reported to improve bud fruitfulness under conditions that would otherwise reduce reproductive development (Menary, 1979). Paclobutrazol is transported almost exclusively in the xylem and therefore moves predominantly from roots to shoots. Consequently, it is largely excluded from developing fruit tissues and frequently improves fruit growth indirectly by suppressing competing vegetative sinks. In contrast, fruit development is particularly sensitive to CCC (Considine, 1983). However, CCC is metabolised relatively rapidly and may therefore be better suited to targeting specific developmental phases of vine growth (B.G. Coombe, pers. comm.).

Two other gibberellin-biosynthesis inhibitors have also been assessed for viticultural applications: prohexadione (Li et al., 2024; Thomidis et al., 2018) and uniconazole (Ledbetter and Shonnard, 1992; Rubio et al., 2019).

4.6.2 Abscisic Acid

Abscisic acid (ABA) is a naturally occurring plant growth regulator that plays a central role in stress adaptation and short-term responses to water deficit through its regulation of stomatal aperture. In table grape production it is commonly used to improve berry colour development in hot climates. However, ABA also contributes to shoot maturation, preparation for leaf abscission and the regulation of shoot extension growth. In grapevines generally, ABA applications have been shown to improve cane maturation and cold tolerance by slowing shoot growth, enhancing periderm development and promoting leaf abscission when applied at or after veraison (Zhang and Dami, 2012; Zhang et al., 2011). ABA has also been reported to promote reserve accumulation (Rubio et al., 2019). These observations suggest that ABA may have value during the formation-to-pruning transition, where the objectives are to slow vegetative growth, promote cane maturation, enhance reserve accumulation and prepare the vine for shutdown. Surprisingly, reports evaluating ABA specifically for this purpose in tropical viticulture appear to be lacking.

4.6.3 Ethylene

Ethylene is the principal regulator of abscission but is only effective when the abscission zone has been conditioned to respond (Hendgen et al., 2021). It is also used to suppress shoot extension growth (Shulman, 1982; Shulman et al., 1980). Activation of the abscission zone requires a reduction in auxin synthesis and export from the leaf blade. This process occurs naturally during aging and may also be induced by stress or shortening day length. Ethylene additionally supports cane maturation and radial stem growth (Bondada and Shutthanandan, 2012). As a gas, however, its practical use is largely restricted to enclosed environments such as ripening rooms. In viticulture it is therefore typically applied as ethephon, which decomposes within the plant to release ethylene *in situ*, or as its metabolic precursor, ACC.

Ethephon

Ethephon is a remarkably difficult compound to use reliably because its performance is highly sensitive to environmental conditions and spray formulation. At temperatures below approximately 17°C, insufficient ethylene may be released to generate an adequate response (Clore et al., 1970). Conversely, at temperatures above approximately 32°C, decomposition may occur so rapidly that insufficient active ingredient penetrates the tissue (Biddle et al., 1976). The spray solution should ideally have a pH of approximately 6 to slow decomposition (Hirschfeld and Lavee, 1980). High relative humidity may also increase ethylene loss and reduce spray effectiveness (Klein et al., 1979).

Potassium iodide and urea are frequently included as adjuvants. Both act partly through tissue injury and desiccation, which may accelerate abscission. However, rapid defoliation may come at the expense of the normal senescence process and the associated recycling of mineral nutrients required for the following growth cycle.

1–Aminocyclopropane–1–Carboxylic Acid (ACC)

ACC is the naturally occurring immediate precursor of ethylene and the principal form in which the hormone is transported within the plant. It is more stable than ethephon and has been reported to provide more reliable responses under some circumstances (Accede®). ACC has been used successfully to enhance berry colour development in table grapes (de Aguiar

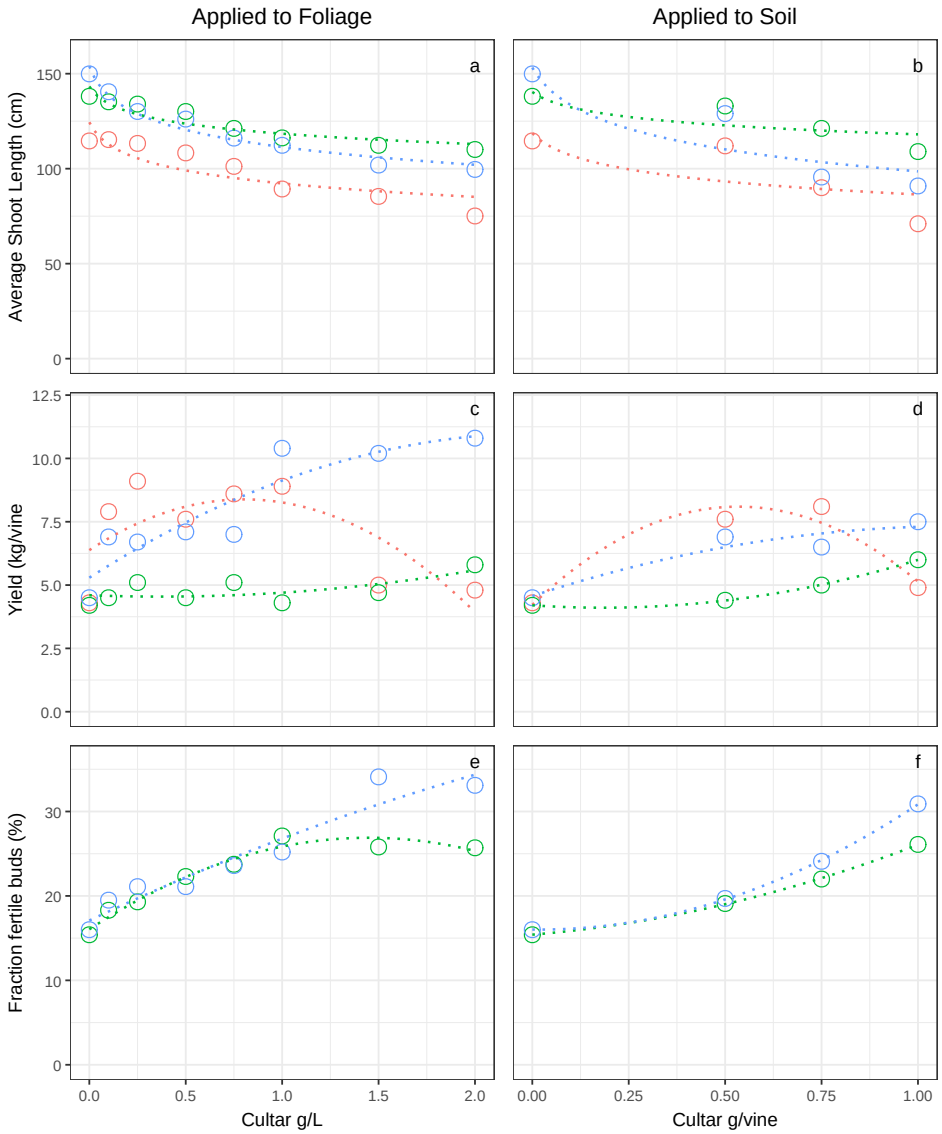


Figure 4.8: Response of grapevines to Cultar® applied either as a canopy spray or via drip irrigation to the soil, 21 days before bud burst. Responses measured included shoot extension, yield and apparent bud fertility. Treatments: ◯ Applied Year 1, measured Year 1; ◯ applied Year 1, measured Year 2; ◯ applied Year 1 and Year 2, measured Year 2. Fitted lines: a,b; $y \sim \log(x + 0.05)$, c:f; $y \sim x + x^2$ (Table 5 Shaltout et al., 1988).

et al., 2024). It has also been applied in combination with jasmonic acid to promote berry abscission (Fidelibus et al., 2022). Consequently, treatments intended to induce leaf abscission are most appropriately applied after harvest.

4.6.4 Conclusions

Collectively, these plant growth regulators provide tools for modifying the competitive relationships between vegetative growth, reproductive growth and reserve accumulation. Their importance in tropical viticulture lies not simply in controlling shoot extension, but in improving the allocation of assimilates to developing inflorescences, maturing canes and perennial storage tissues. In this respect, PGRs complement irrigation, pruning and shutdown management practices by helping to recreate physiological conditions that occur naturally in temperate viticultural systems.

4.7 Field Evaporative Cooling

The literature reviewed suggests that field evaporative cooling may represent one of the most important opportunities for improving productivity in northern Australian viticulture (Table 4.1. Unlike shading (Table 4.2), which reduces both temperature and photosynthetically active radiation, evaporative cooling can substantially reduce tissue temperature while maintaining

high light interception. This distinction is particularly important because inflorescence initiation and development appear to require high light intensity but are negatively affected by very high temperatures.

4.8 Case Study: The Climate of Roebuck Plains and the Need for Cooling

A previous review assessed the relationships between temperature, radiation, and grapevine productivity, with particular attention to inflorescence primordium development during both bud formation and subsequent bud burst (Figure 3.11, Considine (2024)). Earlier studies generally reported positive effects of high temperature and high irradiance on inflorescence development. However, more recent work suggests that inflorescence initiation may exhibit an optimum temperature of approximately 25°C while still requiring high light intensity (Sanchez and Dokoozlian, 2005). Additionally, elevated temperatures immediately before and during bud burst have been shown to reduce inflorescence development (Petrie and Clingeleffer, 2005). Given that inflorescence development is frequently poorer in tropical production regions than in conventional temperate viticultural regions, it is reasonable to consider heat stress as a major factor limiting productivity in tropical viticulture (Considine, 2024). Similar constraints may also occur in warm subtropical regions such as Carnarvon (*e.g.* Dahal et al., 2022).

4.8.1 The Environment

Evaporative cooling is a well-established technology with a long history of application in residential, commercial, and agricultural environments. Its effectiveness has been extensively modelled over a wide range of temperature and humidity conditions (*e.g.* Rabbi et al., 2019; Sureshkumar et al., 2008a,b). Predominantly this research has focussed on protected cropping in which it is a well-established and widely used practice (*e.g.* Rabbi et al., 2019). Fewer studies exist whereby unprotected crops are the target.

Analysis of weather data from the DPIRD Skuthorpe weather station during 2023 indicates that maximum daily temperatures commonly exceeded the proposed optimum temperature for inflorescence initiation and development (Figures 4.9 and 4.11). These observations suggest substantial scope for cooling to improve vine performance. Relative humidity values were also generally favourable for evaporative cooling, with daytime humidity commonly below 40% (Figure 4.10). Similarly, daily maximum vapour pressure deficits frequently exceeded the range generally considered optimal for photosynthesis and carbon assimilation (Figure 4.12). Together, these observations indicate that field evaporative cooling should be both technically effective and physiologically beneficial under Roebuck Plains conditions.

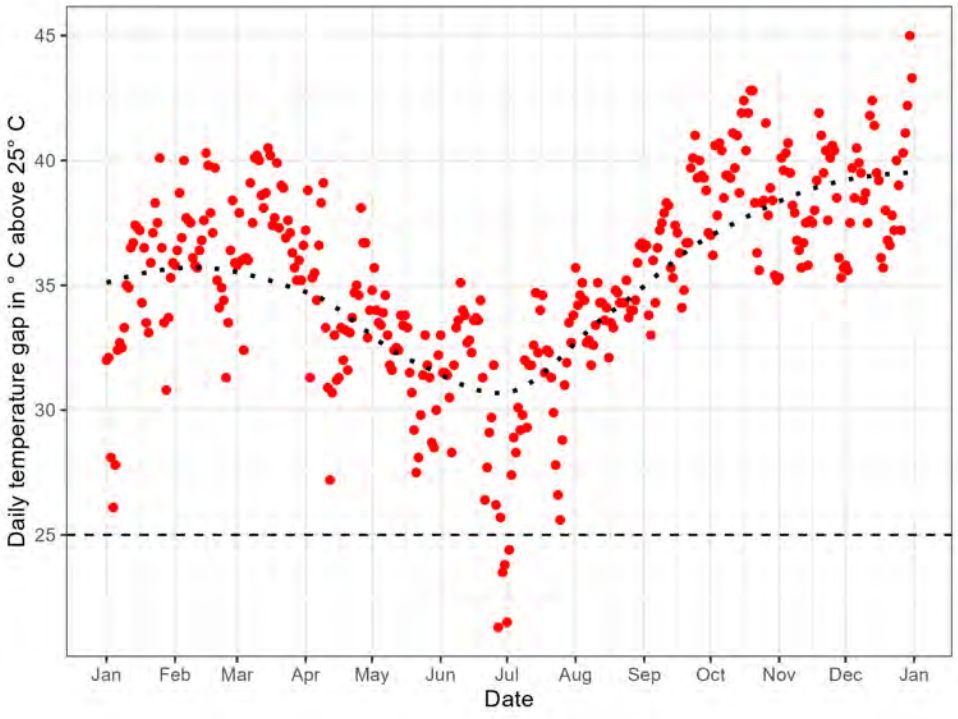


Figure 4.9: Daily maximum temperature for the year 2023. The dashed horizontal line represents the suggested optimum temperature for inflorescence initiation and development. Higher temperatures reduce inflorescence development (Sanchez and Dokoozlian, 2005). Data from BR10, Skuthorpe, DPIRD.

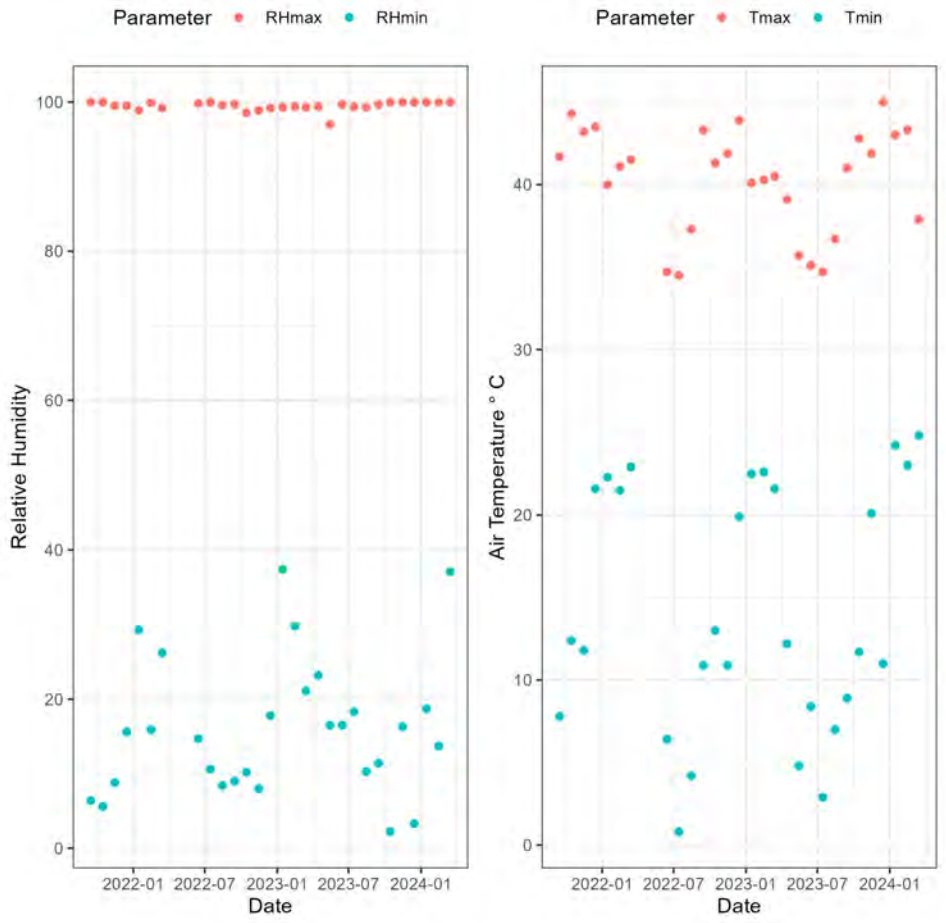


Figure 4.10: Monthly average Relative Humidity and Temperature values for the DPIRD Skuthorpe weather station (BR010)

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4.8.2 Field Evaporative Cooling

The literature shows remarkable consistency regarding the effectiveness of evaporative cooling. Depending on system design and environmental conditions, reductions of 5 to 15°C in tissue temperature have been achieved. Importantly, the greatest cooling occurs directly on wetted plant surfaces rather than through cooling of the surrounding air. Reported benefits include increased berry size, improved assimilation, reduced evaporative demand, reduced heat damage, improved bud burst, and, in some cases, substantial increases in yield. Collectively, these studies suggest that field evaporative cooling offers a practical means of reducing thermal stress while maintaining high levels of light interception. However, there may be circumstances that favour fogging which, if correctly applied, leads to low levels of leaf wetting and thus lowered disease risk *c.f.* surface wetting methods (Zhang and Shipp, 2002). In either approach water quality is a serious concern but volumes are generally low enough and the returns sufficient to justify water purification if necessary (e.g. as widely used commercially in Israel and Egypt).

4.8.3 Shading

The evidence concerning shading is considerably less favourable than that for evaporative cooling. Multiple studies report substantial reductions in bud fertility and increases in primary bud necrosis when shading exceeds approximately 50%. In several instances, reductions in fruitfulness persisted into subsequent production cycles. While shade cloth may reduce canopy temperature, these benefits often appear outweighed by reductions in carbon assimilation and reproductive development.

Coloured photoselective nets may provide a partial exception because they modify spectral quality while maintaining relatively high light transmission. These systems warrant further investigation in tropical viticulture, particularly where cyclone risk can be managed (Shahak et al., 2016, 2008). Reflective mineral coatings, including kaolin-based products, generally provide only modest reductions in tissue temperature and appear substantially less effective than evaporative cooling (Table 4.3). Benefits are often inconsistent, cultivar dependent, and reduced under water-deficit conditions. Overall, the available evidence strongly favours field evaporative cooling as the most promising strategy for managing extreme heat in northern Australian vineyards.

Table 4.1: A summary of research on the application of evaporative cooling to field-grown vineyards/vines.

Method	Summary	Reference
Foggers	Use of in-canopy foggers to reduce heat damage to ripening bunches. On for 2 min, off for 1 min when air temperature >33 °C and RH <55%. Over 44 days delivered 145 mm resulting in a temperature drop of −6 °C to −9 °C.	Bonini et al. (2025).
Micro-sprinklers	Use of micro-sprinklers during periods when temperature exceeded 32°C lowered temperature of air, leaf, fruit and soil by 5 to 10°C leading to delayed maturity but larger berries and greater shoot growth.	Aljibury et al. (1975)
Micro-sprinklers	Used an energy balance model to maximise efficiency, Netafin Coolnet Pro sprinklers. Sprinklers set to operate at T => 37°C. A drop of about 5°C achieved within the canopy. Berry mass increased. Greatest cooling occurred on wet surfaces.	Caravia et al. (2017)
Overhead sprinklers	Sprinklers operated 3 min. on, 15 min. off cooled the air 4 to 6°C and the plants by 5 to 14°C	Gilbert et al. (1970)
Micro-sprays	3 Lh^{-1} at 1 m intervals. On for 30 s then off for 5 min. when leaf canopy temperature => 35°C. Leaf temperature reduced by as much as 8°C. Berry diameter were increased as was net assimilation	Greer and Weedon (2014a)
Single nozzle, knocker	16/14 min. on/off. T => 26.7°C. Maximum reduction of canopy T was 8.9°C and average was 3.3°C. Potato crop canopy <= 26.7°C while bean canopy occasionally exceeded that value. Soil temperature also reduced by *ca* 1°C.	Hobbs (1973)
Misting sprinkler	Sprinkler operated by a 'hemp string', on at T => 30°C. Leaves and fruits 3 to 22°C cooler than controls. Fruit yield and quality improved.	Kliewer and Schultz (1973)
Misting sprinklers	Winter, T => 8°C. Either 40s on, according to difference between 'wet' and 'dry' plots or at 6 min. intervals. Bud burst was delayed by 4 to 7 days.	Natali et al. (1987)
Overhead micro-sprinklers	Temperature of buds exposed to light was lowered from 30 to 16°C and that of shaded buds from 25 to 13°C. Increased yields by as much as 46% when combined with HCN. 1.5 min. on, 15 to 20 $min.$ off.	Nir et al. (1988)
Sprinklers vs fogging	A review of technologies focusing on enclosed systems, polyhouses, glasshouses.	Rabbi et al. (2019)
Overhead Micro-sprinklers	5 min. on, 15 min. off, T => 30°C (day), T => 20°C (evening). Fruit surface temperature reduced, cyclically by about 6°C.	van den Dool (2006)
Overhead micro-sprinklers	Fruit surface temperature reduced by about 10°C. Transpiration per hour during spray interval reduced by 30 to 50%. 2.4 mm/h, 15 min. on when T => 34°C	Green et al. (2014)

4.9 Brief Review of Technologies and Limitations

The literature suggests that the benefits obtained through cooling the air surrounding the canopy are relatively modest, typically no more than about 5°C. While any reduction in temperature may be beneficial, considerably greater cooling can be achieved through evaporation directly from plant surfaces. This principle underpins evaporative cooling systems used in apple production, where the objective is to cool the fruit and foliage rather than the surrounding air (*e.g.* Goodwin, 2017). Results reported by Kliewer and Schultz (1973), Greer and Weedon (2014a), and Caravia et al. (2017) demonstrate that temperature reductions exceeding 15°C can be achieved on wetted plant surfaces under suitable environmental conditions. However, all authors noted substantial variation in the distribution of cooling within the canopy because wetting itself was uneven. This limitation remained evident even when emitters were located within the canopy rather than above it, the more conventional arrangement. More uniform cooling may be achievable by locating emitters beneath the canopy in addition to, or instead of, above-canopy installations. The ideal arrangement may involve both positions, ensuring that exposed leaves and fruit are cooled while also providing cooling of developing buds and shoots within the canopy. During bud burst, however, emitters located above the canopy are likely to be more effective because of greater exposure of developing shoots and buds.

Current recommendations regarding droplet size have largely been developed for cooling air spaces occupied by humans or livestock and may not be optimal for cooling grapevine tissues. Relatively fine droplets rapidly increase local humidity, reducing the vapour-pressure gradient that drives evaporation from plant surfaces and thereby limiting tissue cooling (Caravia et al., 2017). Optimisation of droplet size, application frequency, and emitter placement for vineyard cooling remains an important research requirement.

The period of greatest potential benefit appears to commence around EL12 and continue for approximately 10 weeks, although Buttrose (1969) recommended a period closer to 13 weeks to maximise benefits to inflorescence development. Much of the existing research on evaporative cooling is difficult to apply directly to viticulture because it focuses primarily on reducing

Table 4.2: A summary of research on the application of shade cloth to field-grown vineyards/vines.

Method	Summary	Reference
Shadecloth	62% exclusion shadecloth: horizontal, canopy, full canopy, soil. Temperature reduced by 1.5 *to* 2.5°C varying with T_{max}. Overhead was the best system reducing water deficit stress and increasing photosynthesis	Caravia et al. (2016)
Shadecloth	60% shading raised PBN from 0.6% to 26%. It also increased NH_4^+ which was also associated with increased levels of PBN	Gu et al. (1996)
Shadecloth	70% Reduced yield in the season of application and fruitfulness in the following year was severely depressed	May and Antcliff (1963)
Shadecloth	80% Had serious detrimental effects on growth and productivity in the following growth cycle	McArtney and Ferree (1999)
Shadecloth	52, 25 or 14% transmission. Even the lowest shading level reduced bud fertility from 48 to 11% and raised PBN from 15 to 39%	Perez and Kliewer (1990)
Shadecloth	50% in combination N nutrition. Shaded vines produced less dry matter and reduced assimilation	Porro et al. (2001)
Shadecloth	92% exclusion increased PBN substantially if applied during the phase of bud emergence	Vasudevan et al. (1998)
Hail Netting	White HDPE monofilament knitted netting (12 mm Q Net). Small reduction in T, 24% reduction in direct solar radiation. Largest surface ΔT, 14 *to* 20°C, average 5 *to* 8°C.	Goodwin et al. (2018)
Shadecloth	40%, grey, blue, red, white (20%, control). Red and blue ↓ PAR 27%, blue net ↑ fruit wt and PHS (30%, ↑ leaf area. Blue ↑ B:R and ↓ R:FR	Bastías et al. (2012)
Shadecloth	Yellow, Red, blue, grey. 15 to 30% white or pearl advanced maturity, red delayed, blue reduced vegetative growth	Shahak et al. (2008)
Shadecloth	Both yellow and red shadecloths reduced pruning wt of 'Red globe'. Nice table of spectral analysis under coloured shadecloths	Shahak et al. (2016)

Table 4.3: A summary of research on the application of reflective coatings to field-grown vineyards/vines.

Method	Summary	Reference
Kaolin Particle film	Kaolin particle film effectiveness was greatest on well-watered vines and failed to offset the impact of water deficit. Its effectiveness was also cultivar dependent. The effects were relatively minor	Glenn et al. (2010)
Kaolin Particle Film	The film reduced the time leaf temperature exceeded 30°C but the result depended on vine direction. It also reduced assimilation.	Shellie and King (2013)
Kaolin ± Zeolites	Leaf temperature was reduced by only 1 to 2°C but fruit temperature by as much as 5 to 6°C. There was little impact on assimilation or solute accumulation or berry mass. However, colour was improved in some instances.	Valentini et al. (2021)

ambient air temperature. Within a grapevine canopy, humidity is often the principal factor limiting evaporative cooling efficiency (Caravia et al., 2017). Consequently, systems designed to maximise evaporation from plant surfaces rather than from airborne droplets are likely to provide superior outcomes.

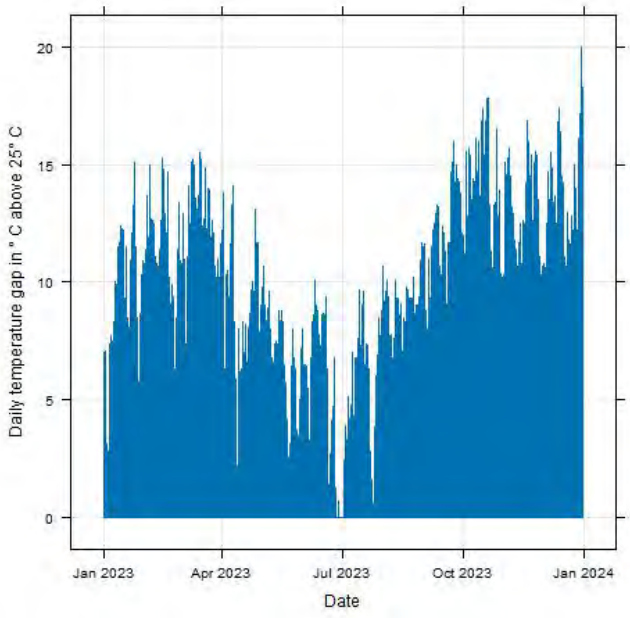


Figure 4.11: Daily maximum gap in temperature between the suggested optimum temperature for inflorescence initiation and development and that observed. Data from BR10, Skuthorpe, DPIRD.

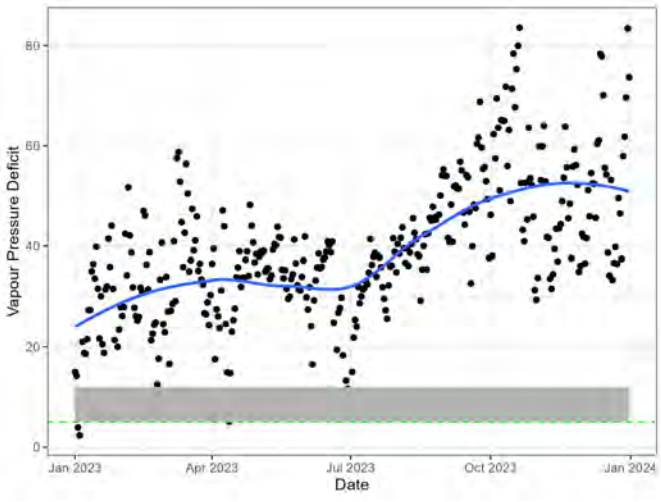


Figure 4.12: Daily maximum vapour pressure deficit for the year 2023. The horizontal grey box represents the optimum range for assimilation of carbon. Data from BR10, Skuthorpe, DPIRD. VPD calculated using a modified Arrhenius equation (Howell and Dusek, 1995).

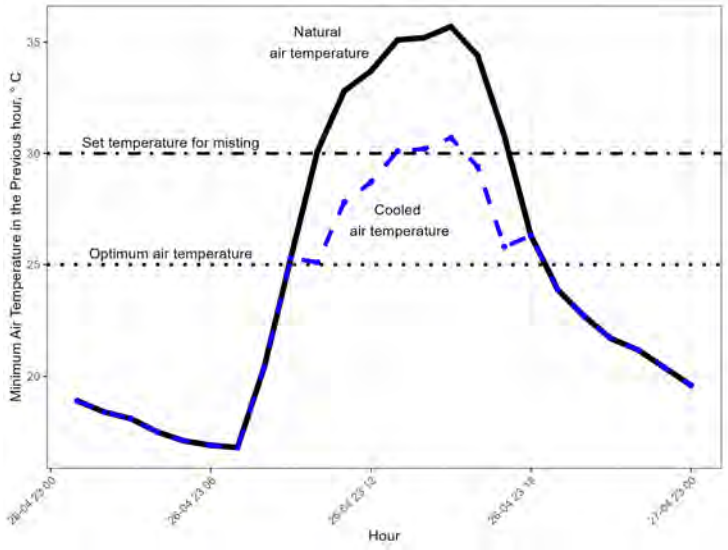


Figure 4.13: The suggested effect of applying a cooling mist to a vine under the environmental conditions that applied on April 26, 2023 at Skuthorpe. The upper, horizontal, dashed line is the suggested set point for commencing cooling and the lower, dotted line, the ideal temperature for inflorescence initiation and development. The dashed blue line is the air temperature expected to be achieved by mist sprinkler cooling. Data courtesy DPIRD.

4.10 Effectiveness of Mist Cooling in Field Conditions

The benefits of evaporative cooling extend beyond grapevines and have been demonstrated in a wide range of horticultural crops under conditions of heat stress.

Crop	Comment	Reference
Apple	48% increase in yield, increased flower production but not fruit set, additive to irrigation	Goode et al. (1979)
Peas	60% mist irrigation reduced leaf temperature and increased vegetative growth and pod yield	Howell et al. (1971)
Tomatoes	31–50% increase in yield; early yield of muskmelon cv. Howell Spartan reduced by 84%, whereas that of Moreton Hybrid increased by 33%; cucumber yields increased by 70%	Bible et al. (1968)
Tomatoes	Improved plant health but no yield response where irrigation was already optimal	Stirzaker et al. (1997)
Potatoes	22% increase in yield	Wheaton and Kidder (1966)
Cauliflower and Lettuce	Improved cauliflower quality	Spears (1967)
Prunes	No significant response	Proebsting and Middleton (1971)
Apples	Reduced physiological disorders; improved colour and fruit size	Unrath and Sneed (1974)

Conclusions:
Across a broad range of horticultural crops, evaporative cooling has generally improved either productivity, product quality, or both. Responses vary depending on species, cultivar, climate, and irrigation management, but yield increases of 20–50% are commonly reported under conditions of heat stress. The consistency of these responses suggests that heat load frequently limits productivity in field-grown crops and supports the hypothesis that cooling may substantially improve vine performance in tropical and subtropical viticulture. The particularly large responses observed in apple production are noteworthy, as these include improvements in flowering and reproductive development rather than simply reductions in fruit damage.

Unlike shading, evaporative cooling reduces tissue temperature without substantially reducing light interception, thereby addressing what appears to be the central physiological challenge of tropical viticulture: maintaining reproductive development under conditions of excessive heat.

The developmental stages most likely to benefit from cooling are inflorescence initiation, inflorescence differentiation within dormant buds, the period immediately preceding bud burst, and the early stages of inflorescence expansion following bud burst. In contrast, evidence suggests that moderate reductions in temperature during berry ripening may primarily affect fruit composition and maturity rate rather than reproductive potential. Consequently, cooling systems should probably be managed with greatest emphasis on the phases influencing bud fruitfulness and inflorescence development.

4.11 Peri-Budburst Inflorescence Development

Relatively little experimental work has been published on the final phase of inflorescence development that occurs during bud burst and the early stages of shoot growth. Nevertheless, the available evidence suggests that temperature during this period may have a substantial influence on the ultimate size and complexity of the inflorescence.

May (1964) compared cool (15/10°C day/night) and mild (22/16°C day/night) temperature regimes and observed a pronounced positive effect of temperature on inflorescence development. In contrast, Petrie and Clingeleffer (2005) found that flower number declined as temperature increased from approximately 14 to 18°C during the period immediately preceding and following bud burst. Similarly, Pouget (1981) reported substantially greater flower numbers at lower temperatures, particularly during the earliest stages of bud burst. For example, Merlot vines maintained at 11°C produced approximately 39 flowers per inflorescence compared with only 11 flowers at 25°C under a 16-hour photoperiod.

Although these studies are few in number and appear, at first glance, to be somewhat contradictory, they collectively indicate that temperature during bud burst has a major influence on inflorescence ramification and flower number. They also suggest that the optimum temperature for peri-budburst development may differ from that for earlier phases of inflorescence initiation and differentiation.

From a practical perspective, the available evidence supports investigation of cooling strategies during the period immediately preceding bud burst and extending through the early stages of shoot development. Sprinkler cooling has already been used successfully to augment winter chilling in subtropical production regions (Allan and Hattingh, 1998), providing additional evidence that cooling during bud burst may be both technically feasible and biologically beneficial. Given the importance of flower number to yield potential, the response of developing inflorescences to temperature during this period should be regarded as a priority area for further research.

The evidence therefore suggests two distinct opportunities for cooling: first during inflorescence initiation and differentiation within the latent bud, and second during bud burst when the final degree of inflorescence ramification and flower development is determined.

4.12 Genetic Resources

Management practices such as pruning, irrigation, plant growth regulators and evaporative cooling may alleviate many of the constraints associated with tropical viticulture. However, genetic improvement provides an additional and potentially more durable solution.

Breeding programs in Brazil have developed grape cultivars with improved productivity under tropical conditions (Ritschel et al., 2010). These programs have incorporated genetic resources from tropical species including *Vitis caribaea*, *V. gigas*, *V. smalliana*, and *V. shuttleworthii*, broadly following concepts originally proposed by Fennell (1948). The objective has been to combine adaptation to tropical environments with commercially acceptable fruit quality.

One outcome of this work is the cultivar BRS Clara (Figure 3.11), which exhibits improved fruitfulness under tropical growing conditions compared with many traditional *V. vinifera* table grape cultivars. The breeding program was also designed to improve resilience to fungal diseases, an important consideration in the wet tropical environments of Brazil, many of which are classified as Aw climates with distinct dry winters and humid summer growing seasons.

The success of these breeding efforts suggests that adaptation to tropical environments is not solely a matter of vineyard management. Genetic variation exists for traits associated with productivity under high-temperature conditions, including inflorescence development, bud fertility and disease tolerance. Consequently, the introduction, evaluation and breeding of adapted germplasm may provide an important complementary strategy for the development of a sustainable table grape industry in northern Australia.

4.13 Vineyard Floor Management

The cultivation of temperate vegetable crops such as potato in the hot tropical environments of Peru and Indonesia has been made possible, in part, through the use of mulches to conserve soil moisture and reduce radiation heating of otherwise bare soil surfaces (*e.g.* Midmore et al., 1986). Similar practices have been recommended for cropping systems in the semi-arid tropics of Australia (Bristow, 1988). Throughout tropical agriculture, mulches are widely used to conserve water, moderate soil temperature and improve soil physical properties, most commonly in the form of crop residues (Bussière and Cellier, 1994).

These same principles are applicable to viticulture. Mulches have been shown to reduce soil temperature, conserve soil moisture and reduce the reflection of solar radiation into the canopy (Gouot-Davoust et al., 2026; Guerra and Steenwerth, 2012). Such effects may be of particular importance in tropical and subtropical vineyards where excessive heat rather than insufficient energy frequently limits productivity.

Soil temperature has a profound influence on the subterranean portion of the vine, which may constitute more than half of the total plant biomass. In hot tropical environments, maintaining moderate soil temperatures can be difficult, particularly in bare vineyards where intense solar radiation directly heats the soil surface. Radiation, rather than air temperature, is the principal driver of soil warming and moisture loss (*e.g.* Midmore et al., 1986). Consequently, practices that intercept solar radiation before it reaches the soil can substantially reduce evaporative losses and improve the root-zone environment (Figure 4.14 and 4.15). In potatoes, shading reduced soil water losses from almost 40% to approximately 15% over a five-day period (Midmore et al., 1986). However, while artificial shading is effective in reducing soil temperatures, excessive shading of the vine canopy can substantially reduce productivity (Greer and Weston, 2010).

Cover crops have become an established component of vineyard floor management, although they are rarely adopted specifically to reduce soil temperature. In the tropical viticulture of Paraná State, Brazil, cover crops are recommended as part of routine management, with jack bean grown during summer and a grass sward maintained through winter (Mariani et al., 2019). Cover crops contribute to integrated pest management by supporting populations of beneficial insects and predators, while also improving soil structure, increasing organic matter, contributing biologically fixed nitrogen, and moderating excessive vine vigour (French et al., 2025; Steenwerth and Belina, 2008). In some situations they have also been associated with reduced incidence of Botrytis bunch rot (Jacometti et al., 2007).

Mulches may provide similar benefits while imposing less competition for water and nutrients. For example, a recent study conducted in an arid region of Turkey found that straw mulch improved soil water retention, increased soil organic matter, reduced leaf temperatures and increased stomatal conductance (Zengin and Sabir, 2022). These observations suggest that vineyard floor management may offer a practical means of improving the vine microclimate while simultaneously enhancing soil function.

Collectively, the evidence suggests that vineyard floor management should be viewed as an integral component of heat-management strategies in northern Australian viticulture. While evaporative cooling directly addresses excessive canopy and bud temperatures, mulches and cover crops can reduce soil temperatures, conserve water and improve root-zone conditions. Used together, these approaches may provide a more complete solution to the challenges imposed by tropical environments.

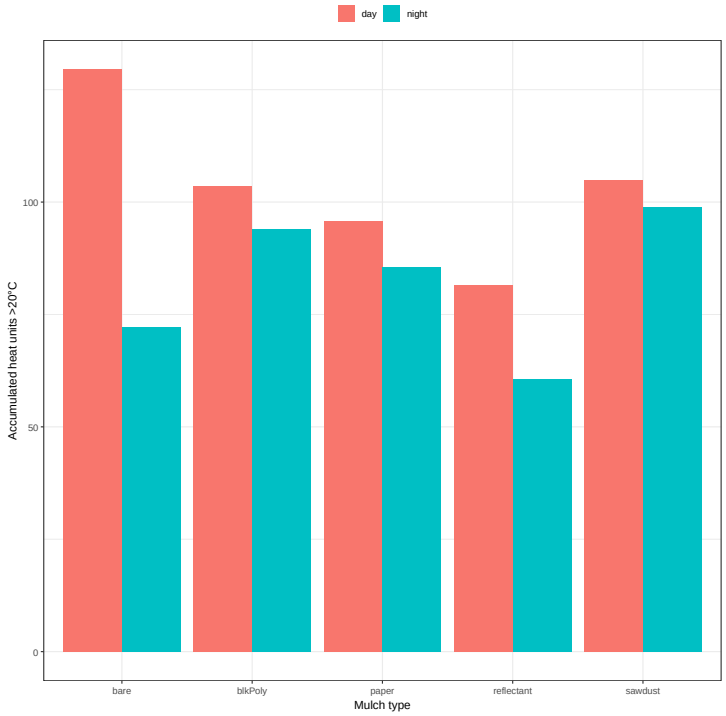


Figure 4.14: Effect of mulch presence and type on soil temperature in a hot tropical environment. Reproduced from Midmore et al. (Fig. 2 1986)

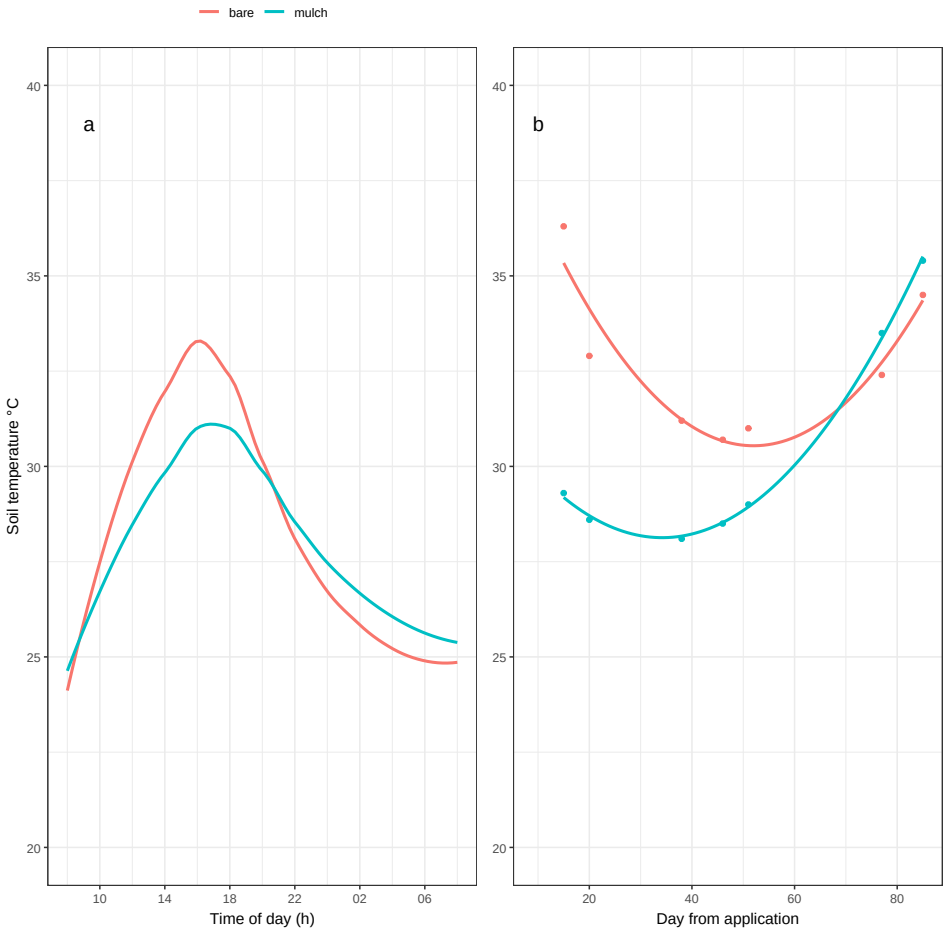


Figure 4.15: Effect of mulch on soil temperature at 15 cm depth in a hot tropical environment. (a) Change in temperate through a day (b) Change in temperature with days after planting a potato crop. Data from Midmore et al. (Figs 2 and 3 1986).

4.14 Supplementary data

Table 4.4: Table S1. Phenological windows and associated timing metrics.

		Window end date						Days to EL				
Site	Prune	EL3	EL12	EL25	EL34	EL38	RainVH	D3	D12	D25	D34	D38
Carnarvon	2025-01-01	Jan-08	Jan-15	Feb-04	Mar-11	Apr-04	0	7	14	34	69	93
Carnarvon	2025-01-15	Jan-21	Jan-28	Feb-17	Mar-25	Apr-20	0	6	13	33	69	95
Carnarvon	2025-01-29	Feb-04	Feb-11	Mar-03	Apr-10	May-10	0	6	13	33	71	101
Carnarvon	2025-02-12	Feb-18	Feb-25	Mar-16	Apr-28	Jun-07	0	6	13	32	75	115
Carnarvon	2025-02-26	Mar-04	Mar-10	Apr-01	May-21	Jul-21	0	6	12	34	84	145
Carnarvon	2025-03-12	Mar-18	Mar-25	Apr-18	Jun-26	Sep-01	0	6	13	37	106	173
Carnarvon	2025-03-26	Apr-02	Apr-10	May-07	Aug-09	Sep-30	0	7	15	42	136	188
Carnarvon	2025-04-09	Apr-17	Apr-26	May-30	Sep-11	Oct-21	0	8	17	51	155	195
Carnarvon	2025-04-23	May-02	May-12	Jun-28	Oct-03	Nov-07	0	9	19	66	163	198
Carnarvon	2025-05-07	May-18	Jun-01	Jul-31	Oct-19	Nov-21	0	11	25	85	165	198
Carnarvon	2025-05-21	Jun-04	Jun-21	Aug-24	Nov-01	Dec-01	0	14	31	95	164	194
Carnarvon	2025-06-04	Jun-21	Jul-13	Sep-09	Nov-11	Dec-10	0	17	39	97	160	189
Carnarvon	2025-06-18	Jul-09	Jul-31	Sep-21	Nov-18	Dec-16	0	21	43	95	153	181
Carnarvon	2025-07-02	Jul-24	Aug-14	Sep-30	Nov-24	Dec-21	0	22	43	90	145	172
Carnarvon	2025-07-16	Aug-06	Aug-25	Oct-07	Nov-30	Dec-26	0	21	40	83	137	163
Carnarvon	2025-07-30	Aug-19	Sep-05	Oct-15	Dec-05	Dec-30	0	20	37	77	128	153
Carnarvon	2025-08-13	Aug-30	Sep-15	Oct-22	Dec-11	Jan-03	0	17	33	70	120	143
Carnarvon	2025-08-27	Sep-12	Sep-26	Oct-30	Dec-17	Jan-08	0	16	30	64	112	134
Carnarvon	2025-09-10	Sep-24	Oct-07	Nov-07	Dec-23	Jan-14	0	14	27	58	104	126
Carnarvon	2025-09-24	Oct-06	Oct-18	Nov-17	Dec-30	Jan-21	0	12	24	54	97	119
Carnarvon	2025-10-08	Oct-19	Oct-29	Nov-26	Jan-06	Jan-29	0	11	21	49	90	113
Carnarvon	2025-10-22	Nov-01	Nov-11	Dec-07	Jan-15	Feb-06	0	10	20	46	85	107
Carnarvon	2025-11-05	Nov-14	Nov-23	Dec-18	Jan-24	Feb-15	0	9	18	43	80	102
Carnarvon	2025-11-19	Nov-27	Dec-06	Dec-29	Feb-03	Feb-25	0	8	17	40	76	98
Carnarvon	2025-12-03	Dec-11	Dec-19	Jan-08	Feb-14	Mar-07	0	8	16	36	73	94
Carnarvon	2025-12-17	Dec-24	Dec-31	Jan-20	Feb-25	Mar-19	0	7	14	34	70	92
Carnarvon	2025-12-31	Jan-06	Jan-13	Feb-02	Mar-10	Apr-02	0	6	13	33	69	92
Emerald	2025-01-15	Jan-21	Jan-27	Feb-16	Mar-25	Apr-21	0	6	12	32	69	96
Emerald	2025-01-29	Feb-04	Feb-11	Mar-03	Apr-12	May-16	0	6	13	33	73	107
Emerald	2025-02-12	Feb-18	Feb-25	Mar-17	May-02	Jun-22	0	6	13	33	79	130
Emerald	2025-02-26	Mar-04	Mar-11	Apr-02	May-30	Aug-11	0	6	13	35	93	166
Emerald	2025-03-12	Mar-19	Mar-26	Apr-20	Jul-14	Sep-12	0	7	14	39	124	184
Emerald	2025-03-26	Apr-02	Apr-10	May-11	Aug-25	Oct-02	0	7	15	46	152	190
Emerald	2025-04-09	Apr-17	Apr-27	Jun-07	Sep-18	Oct-18	0	8	18	59	162	192
Emerald	2025-04-23	May-03	May-15	Jul-12	Oct-03	Oct-30	0	10	22	80	163	190
Emerald	2025-05-07	May-19	Jun-04	Aug-12	Oct-14	Nov-09	0	12	28	97	160	186
Emerald	2025-05-21	Jun-06	Jun-27	Aug-31	Oct-23	Nov-16	0	16	37	102	155	179
Emerald	2025-06-04	Jun-24	Jul-19	Sep-11	Oct-30	Nov-23	0	20	45	99	148	172
Emerald	2025-06-18	Jul-12	Aug-05	Sep-20	Nov-04	Nov-28	0	24	48	94	139	163
Emerald	2025-11-05	Nov-12	Nov-19	Dec-09	Jan-13	Feb-02	0	7	14	34	69	89
Kununurra	2025-01-29	Feb-03	Feb-09	Feb-27	Mar-30	Apr-19	0	5	11	29	60	80
Kununurra	2025-02-12	Feb-17	Feb-23	Mar-13	Apr-14	May-05	0	5	11	29	61	82
Kununurra	2025-02-26	Mar-03	Mar-09	Mar-27	Apr-29	May-23	0	5	11	29	62	86
Kununurra	2025-03-12	Mar-17	Mar-23	Apr-10	May-16	Jun-13	0	5	11	29	65	93
Kununurra	2025-03-26	Mar-31	Apr-06	Apr-25	Jun-05	Jul-08	0	5	11	30	71	104
Kununurra	2025-04-09	Apr-15	Apr-21	May-12	Jun-29	Jul-31	0	6	12	33	81	113
Kununurra	2025-04-23	Apr-29	May-06	May-30	Jul-21	Aug-20	0	6	13	37	89	119
Kununurra	2025-05-07	May-14	May-22	Jun-18	Aug-10	Sep-05	0	7	15	42	95	121
Kununurra	2025-05-21	May-28	Jun-06	Jul-06	Aug-25	Sep-17	0	7	16	46	96	119

Table 4.4: Table S1. Phenological windows and associated timing metrics. *(continued)*

		Window end date						Days to EL				
Site	Prune	EL3	EL12	EL25	EL34	EL38	RainVH	D3	D12	D25	D34	D38
Kununurra	2025-06-04	Jun-13	Jun-23	Jul-23	Sep-07	Sep-27	0	9	19	49	95	115
Kununurra	2025-06-18	Jun-28	Jul-08	Aug-06	Sep-16	Oct-06	0	10	20	49	90	110
Kununurra	2025-07-02	Jul-12	Jul-21	Aug-18	Sep-25	Oct-13	0	10	19	47	85	103
Kununurra	2025-07-16	Jul-26	Aug-04	Aug-30	Oct-03	Oct-21	0	10	19	45	79	97
Kununurra	2025-07-30	Aug-08	Aug-17	Sep-09	Oct-11	Oct-29	0	9	18	41	73	91
Kununurra	2025-08-13	Aug-21	Aug-29	Sep-19	Oct-19	Nov-05	0	8	16	37	67	84
Kununurra	2025-08-27	Sep-03	Sep-10	Sep-28	Oct-28	Nov-14	0	7	14	32	62	79
Mareeba	2025-01-29	Feb-05	Feb-13	Mar-08	Apr-22	May-26	0	7	15	38	83	117
Mareeba	2025-02-12	Feb-19	Feb-27	Mar-23	May-11	Jun-18	0	7	15	39	88	126
Mareeba	2025-02-26	Mar-05	Mar-13	Apr-07	May-31	Jul-13	0	7	15	40	94	137
Mareeba	2025-03-12	Mar-20	Mar-28	Apr-23	Jun-23	Aug-07	0	8	16	42	103	148
Mareeba	2025-03-26	Apr-03	Apr-11	May-10	Jul-16	Aug-30	0	8	16	45	112	157
Mareeba	2025-04-09	Apr-18	Apr-27	May-29	Aug-09	Sep-18	0	9	18	50	122	162
Mareeba	2025-04-23	May-02	May-12	Jun-17	Aug-29	Oct-03	0	9	19	55	128	163
Mareeba	2025-05-07	May-17	May-28	Jul-06	Sep-14	Oct-16	0	10	21	60	130	162
Mareeba	2025-05-21	Jun-01	Jun-13	Jul-25	Sep-28	Oct-27	0	11	23	65	130	159
Mareeba	2025-06-04	Jun-16	Jun-29	Aug-11	Oct-10	Nov-06	0	12	25	68	128	155
Mareeba	2025-06-18	Jul-01	Jul-15	Aug-26	Oct-19	Nov-15	0	13	27	69	123	150
Mareeba	2025-07-02	Jul-16	Jul-30	Sep-07	Oct-28	Nov-24	0	14	28	67	118	145
Mareeba	2025-07-16	Jul-30	Aug-13	Sep-18	Nov-05	Dec-01	0	14	28	64	112	138
Mareeba	2025-07-30	Aug-13	Aug-26	Sep-28	Nov-13	Dec-08	0	14	27	60	106	131
Roebuck	2025-01-29	Feb-04	Feb-10	Feb-27	Apr-01	Apr-21	0	6	12	29	62	82
Roebuck	2025-02-12	Feb-17	Feb-23	Mar-14	Apr-15	May-06	0	5	11	30	62	83
Roebuck	2025-02-26	Mar-04	Mar-10	Mar-28	Apr-30	May-25	0	6	12	30	63	88
Roebuck	2025-03-12	Mar-17	Mar-23	Apr-10	May-17	Jun-15	0	5	11	29	66	95
Roebuck	2025-03-26	Mar-31	Apr-06	Apr-25	Jun-06	Jul-09	0	5	11	30	72	105
Roebuck	2025-04-09	Apr-15	Apr-21	May-12	Jun-29	Aug-02	0	6	12	33	81	115
Roebuck	2025-04-23	Apr-29	May-06	May-30	Jul-23	Aug-24	0	6	13	37	91	123
Roebuck	2025-05-07	May-14	May-22	Jun-18	Aug-13	Sep-11	0	7	15	42	98	127
Roebuck	2025-05-21	May-29	Jun-07	Jul-07	Aug-29	Sep-24	0	8	17	47	100	126
Roebuck	2025-06-04	Jun-13	Jun-23	Jul-24	Sep-12	Oct-06	0	9	19	50	100	124
Roebuck	2025-06-18	Jun-28	Jul-08	Aug-08	Sep-23	Oct-15	0	10	20	51	97	119
Roebuck	2025-07-02	Jul-12	Jul-22	Aug-21	Oct-03	Oct-24	0	10	20	50	93	114
Roebuck	2025-07-16	Jul-26	Aug-05	Sep-02	Oct-12	Nov-01	0	10	20	48	88	108
Roebuck	2025-07-30	Aug-09	Aug-18	Sep-13	Oct-20	Nov-09	0	10	19	45	82	102
Roebuck	2025-08-13	Aug-22	Aug-31	Sep-24	Oct-29	Nov-17	0	9	18	42	77	96
Roebuck	2025-08-27	Sep-04	Sep-12	Oct-04	Nov-07	Nov-26	0	8	16	38	72	91
Roebuck	2025-09-10	Sep-17	Sep-25	Oct-15	Nov-17	Dec-05	0	7	15	35	68	86
StGeorge	2025-01-01	Jan-07	Jan-13	Feb-01	Mar-10	Apr-05	0	6	12	31	68	94
StGeorge	2025-01-15	Jan-21	Jan-27	Feb-16	Mar-27	May-02	0	6	12	32	71	107
StGeorge	2025-01-29	Feb-04	Feb-11	Mar-03	Apr-19	Sep-05	0	6	13	33	80	219
StGeorge	2025-02-12	Feb-18	Feb-25	Mar-19	Jun-01	Oct-06	0	6	13	35	109	236
StGeorge	2025-02-26	Mar-04	Mar-12	Apr-06	Sep-22	Oct-27	0	6	14	39	208	243
StGeorge	2025-04-09	Apr-19	May-03	Sep-21	Nov-13	Dec-07	0	10	24	165	218	242
StGeorge	2025-04-23	May-08	Jun-14	Oct-06	Nov-22	Dec-15	0	15	52	166	213	236
StGeorge	2025-05-07	Jun-10	Sep-05	Oct-16	Nov-29	Dec-21	0	34	121	162	206	228
StGeorge	2025-05-21	Aug-24	Sep-16	Oct-22	Dec-03	Dec-25	0	95	118	154	196	218
StGeorge	2025-06-04	Sep-03	Sep-22	Oct-25	Dec-06	Dec-27	0	91	110	143	185	206
StGeorge	2025-06-18	Sep-07	Sep-24	Oct-26	Dec-07	Dec-28	0	81	98	130	172	193
StGeorge	2025-07-02	Sep-08	Sep-25	Oct-27	Dec-07	Dec-29	0	68	85	117	158	180
StGeorge	2025-07-16	Sep-08	Sep-25	Oct-27	Dec-08	Dec-29	0	54	71	103	145	166

Table 4.4: Table S1. Phenological windows and associated timing metrics. *(continued)*

		Window end date						Days to EL				
Site	Prune	EL3	EL12	EL25	EL34	EL38	RainVH	D3	D12	D25	D34	D38
StGeorge	2025-07-30	Sep-10	Sep-26	Oct-27	Dec-08	Dec-30	0	42	58	89	131	153
StGeorge	2025-08-13	Sep-13	Sep-28	Oct-29	Dec-09	Dec-30	0	31	46	77	118	139
StGeorge	2025-08-27	Sep-17	Oct-01	Oct-31	Dec-11	Jan-01	0	21	35	65	106	127
StGeorge	2025-09-10	Sep-26	Oct-07	Nov-05	Dec-15	Jan-04	0	16	27	56	96	116
StGeorge	2025-09-24	Oct-06	Oct-16	Nov-12	Dec-20	Jan-09	0	12	22	49	87	107
StGeorge	2025-10-08	Oct-18	Oct-27	Nov-21	Dec-28	Jan-16	0	10	19	44	81	100
StGeorge	2025-10-22	Oct-30	Nov-08	Nov-30	Jan-04	Jan-25	0	8	17	39	74	95
StGeorge	2025-11-05	Nov-13	Nov-20	Dec-12	Jan-14	Feb-04	0	8	15	37	70	91
StGeorge	2025-11-19	Nov-26	Dec-03	Dec-23	Jan-25	Feb-16	0	7	14	34	67	89
StGeorge	2025-12-03	Dec-10	Dec-16	Jan-04	Feb-07	Mar-01	0	7	13	32	66	88
StGeorge	2025-12-17	Dec-23	Dec-30	Jan-17	Feb-20	Mar-16	0	6	13	31	65	89
StGeorge	2025-12-31	Jan-05	Jan-11	Jan-30	Mar-07	Apr-02	0	5	11	30	66	92
TiTree	2025-01-01	Jan-06	Jan-12	Jan-30	Mar-03	Mar-25	0	5	11	29	61	83
TiTree	2025-01-15	Jan-21	Jan-26	Feb-13	Mar-20	Apr-15	0	6	11	29	64	90
TiTree	2025-01-29	Feb-04	Feb-10	Feb-28	Apr-07	May-16	0	6	12	30	68	107
TiTree	2025-02-12	Feb-18	Feb-24	Mar-15	Apr-30	Aug-22	0	6	12	31	77	191
TiTree	2025-02-26	Mar-04	Mar-10	Mar-31	Jul-18	Sep-22	0	6	12	33	142	208
TiTree	2025-03-12	Mar-18	Mar-25	Apr-19	Sep-10	Oct-12	0	6	13	38	182	214
TiTree	2025-03-26	Apr-03	Apr-11	May-21	Oct-02	Oct-28	0	8	16	56	190	216
TiTree	2025-04-09	Apr-18	Apr-29	Aug-12	Oct-17	Nov-09	0	9	20	125	191	214
TiTree	2025-04-23	May-05	May-25	Sep-09	Oct-28	Nov-19	0	12	32	139	188	210
TiTree	2025-05-07	May-27	Jul-26	Sep-22	Nov-04	Nov-27	0	20	80	138	181	204
TiTree	2025-05-21	Jul-09	Aug-19	Sep-29	Nov-09	Dec-01	0	49	90	131	172	194
TiTree	2025-06-04	Aug-03	Aug-30	Oct-03	Nov-13	Dec-04	0	60	87	121	162	183
TiTree	2025-06-18	Aug-13	Sep-03	Oct-05	Nov-15	Dec-06	0	56	77	109	150	171
TiTree	2025-07-02	Aug-17	Sep-05	Oct-07	Nov-16	Dec-07	0	46	65	97	137	158
TiTree	2025-07-16	Aug-22	Sep-07	Oct-08	Nov-17	Dec-08	0	37	53	84	124	145
TiTree	2025-07-30	Aug-28	Sep-11	Oct-11	Nov-19	Dec-10	0	29	43	73	112	133
TiTree	2025-08-13	Sep-03	Sep-16	Oct-14	Nov-21	Dec-12	0	21	34	62	100	121
TiTree	2025-08-27	Sep-10	Sep-22	Oct-19	Nov-25	Dec-16	0	14	26	53	90	111
TiTree	2025-09-10	Sep-21	Oct-01	Oct-26	Dec-01	Dec-21	0	11	21	46	82	102
TiTree	2025-09-24	Oct-03	Oct-11	Nov-03	Dec-09	Dec-29	0	9	17	40	76	96
TiTree	2025-10-08	Oct-16	Oct-24	Nov-14	Dec-18	Jan-06	0	8	16	37	71	90
TiTree	2025-11-19	Nov-25	Dec-02	Dec-20	Jan-20	Feb-08	0	6	13	31	62	81
TiTree	2025-12-03	Dec-09	Dec-15	Jan-01	Feb-01	Feb-21	0	6	12	29	60	80
TiTree	2025-12-17	Dec-22	Dec-29	Jan-14	Feb-15	Mar-08	0	5	12	28	60	81
TiTree	2025-12-31	Jan-04	Jan-10	Jan-28	Mar-02	Mar-23	0	4	10	28	61	82

Chapter 5

Climate and Ecosystem Analysis: Methods and Sources: A Framework for Agro–Climate Characterisation

Climate and the manner in which plants adapt to particular climatic conditions form the core of this report. This section provides the methodology underpinning the analyses presented in Chapter 2 in particular. This is a summary of the key data sources, processes and analyses rather than a detailed explanation. Further information if required is available from the author.

5.1 Functional Traits

Functional trait analysis provides a means of linking environmental conditions to plant performance and adaptation. In this study, climatic and ecological variables were selected on the basis of their likely influence on grapevine productivity, phenology and resource use. The framework adopted draws upon the principles developed for plant functional trait analysis and ecological classification systems (Cornelissen et al., 2003; Group, 2017; Pérez-Harguindeguy et al., 2013).

5.1.1 Site Selection

Australian study locations were compiled from Australian Table Grape Association (ATGA) production regions together with additional sites identified through industry knowledge. Where a particular vineyard was known, its location was expanded to a circular buffer of 10 km radius in order to capture the environmental characteristics of the surrounding production district. Geographic coordinates and elevation data were obtained using Google Earth™ Pro.

International reference sites were selected to provide climatic, ecological and evolutionary context. Genomic evidence suggests that cultivated table grapes originated in the Levant through domestication of *Vitis vinifera* subsp. *sylvestris* (Dong et al., 2023; Negrul, 1938).

Wine grape domestication is believed to have occurred independently within the Caucasus, and two sites documented by Pipia et al. (2012) were included to represent this secondary centre of domestication. Both domestication centres were considered relevant because many modern table grape cultivars contain ancestry derived from both lineages (Dong et al., 2023). The natural habitat of *Vitis vinifera* subsp. *sylvestris* is associated predominantly with river valleys and stream systems, often at moderate elevations. Accordingly, contemporary production sites within the Levant were included as representative of environments broadly consistent with the historical distribution of wild grapevine populations (Ghantous et al., 2023; Merheb et al., 2025).

Although tropical table grape production has developed in countries such as India and Venezuela, Petrolina in northeastern Brazil was selected as the primary tropical benchmark because it represents one of the world's most successful examples of commercial tropical viticulture (Camargo, 2007). Additional Brazilian sites spanning

a range of climatic zones were included to provide perspective on the environmental diversity within a nation that has pursued extensive breeding and agronomic adaptation to low-latitude production systems.

In total, 32 locations were analysed, comprising 19 Australian production regions and 13 international reference sites (Table 5.1).

Climate data for Australian locations were obtained from the SILO database using point-extraction methods implemented through WeatherOz (Pires et al., 2025; Projections and Team, 2024). Data were extracted for the period 1 January 2000 to 31 December 2025. Equivalent data for international locations were obtained from the ERA5 reanalysis archive via Open-Meteo for the same period (ECMWF, 2026).

Daily values of relative humidity corresponding to maximum and minimum air temperature were derived from hourly SILO and ERA5 records to ensure consistency between datasets. These values were subsequently used to calculate saturation vapour pressure, actual vapour pressure and vapour pressure deficit (VPD).

Saturation vapour pressure:

$$e_s(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right)$$

Actual vapour pressure:

$$e_a = \frac{e_{s,tmin}\left(\frac{RH_{tmin}}{100}\right) + e_{s,tmax}\left(\frac{RH_{tmax}}{100}\right)}{2}$$

Mean saturation vapour pressure:

$$e_s = \frac{e_{s,tmin} + e_{s,tmax}}{2}$$

Vapour pressure deficit:

$$VPD = e_s - e_a$$

5.1.2 Curve Fitting

Temperature responses were analysed using Arrhenius-type functions of the form

$$A(T) = A_0 \exp\left(-\frac{E_a}{RT}\right),$$

where

- T is absolute temperature (K),
- E_a is activation energy (J mol^{-1}),
- R is the universal gas constant (8.314 J mol^{-1} K^{-1}), and
- A_0 is a fitted scaling constant.

5.1.3 Mapping

Maps were produced within the R environment using the packages *rnaturalearth*, *rnaturalearthdata*, *sf*, *terra* and *ggplot2* (**?**). Geographic processing and visualisation were undertaken in both R and QGIS™ (https://qgis.org).

Table 5.1: Table of locations used in these analyses

Site	Latitude	Longitude	Elevation (m)	Country	Region
Applethorpe	-28.64	151.846	821	Aust.	Aust.
Carnarvon	-24.85	113.72	14	Aust.	Aust.
Coolup	-32.73	115.9	23	Aust.	Aust.
Echuca	-36.16	144.7	98	Aust.	Aust.
Ellerslie	-33.82	142.028	41	Aust.	Aust.
Emerald	-23.5	148.13	184	Aust.	Aust.
Gingin	-31.447	115.98	114	Aust.	Aust.
Griffith	-34.31	146.17	129	Aust.	Aust.
Kununurra	-15.71	128.71	106	Aust.	Aust.
Mareeba	-17.064	145.32	507	Aust.	Aust.
Menindee	-32.34	142.43	62	Aust.	Aust.
Robinvale	-34.63	142.76	73	Aust.	Aust.
Roebuck	-17.85	122.48	52	Aust.	Aust.
St George	-28.09	148.5	200	Aust.	Aust.
Sunraysia	-34.38	142.17	57	Aust.	Aust.
Swan Valley	-31.86	115.99	13	Aust.	Aust.
TiTree	-22.46	133.64	573	Aust.	Aust.
Waikerie	-34.18	139.96	46	Aust.	Aust.
Woorinen	-35.26	143.46	62	Aust.	Aust.
Petrolina	-9.34	-40.58	382	Brazil	South America
Joao Pinheiro	-17.4	-46.1	760	Brazil	South America
Limoeiro do Norte	-5.1	-38.0	70	Brazil	South America
Irece	-11.2	-41.5	747	Brazil	South America
Jales	-20.2	-50.3	483	Brazil	South America
Londrina	-23.2	-51.1	566	Brazil	South America
Gardabani	41.37	45.073	272	Georgia	Caucasus
Iori	41.52	45.09	324	Georgia	Caucasus
Canicatti	37.37	13.84	546	Italy	Mediterranean
Ar Aramtha	32.56	35.96	509	Jordan	Levant
Kanafar	33.64	35.72	1020	Lebanon	Levant
Taanayel	33.7	35.8	850	Lebanon	Levant

5.1.4 Köppen–Geiger Assignment

Climate classifications were assigned using the 1 km global Köppen–Geiger dataset developed by Beck et al. (2023). Classification values were extracted for each location and a surrounding 10 km buffer. The classification occupying the greatest proportion of pixels within the buffer was assigned to the site together with its

proportional frequency.

5.1.5 Interim Biogeographic Regionalisation for Australia

Australian bioregions were assigned using Version 7.1 of the Interim Biogeographic Regionalisation for Australia (IBRA) database (Thackway and Cresswell, 1995).

5.1.6 Australian Vegetation Classification

The pre-1750 distribution of Australian vegetation (Group, 2017) was analysed using the *terra* package within R and visualised using QGIS™. Data were aggregated from the original 100 m resolution to 1 km resolution to facilitate processing and mapping. Analyses were restricted to the 31 Major Vegetation Groups.

5.1.7 Climate Analysis by Location

The 32 locations were classified according to latitude, Köppen–Geiger climate class (Beck et al., 2023; Rubel and Kottek, 2010), Australian bioregion (Thackway and Cresswell, 1995), and Australian Major Vegetation Group (Group, 2017). In addition to these established classifications, a purely data-driven grouping was developed using K-means clustering implemented through the R package *cluster* (version 2.1.8.2). The optimum number of clusters was evaluated using the elbow, silhouette and gap statistics.

5.1.8 Climate-Related Statistics

In addition to the raw climatic variables supplied by SILO and ERA5, a series of derived variables relevant to grapevine physiology and productivity were calculated:

Value	Abbreviation	Calculation
Daily temperature range	drt	$T_{max} - T_{min}$
Heat thresholds		
	hot_35	$T_{max} \geq 35°C$
	hot_37	$T_{max} \geq 37°C$
	hot_40	$T_{max} \geq 40°C$
Cold nights		
	cold_night_le7	$tmin \leq 7$
	cold_night_le10	$tmin \leq 10$
	cold_night_le13	t$min \leq 13$
Warm nights		
	warm_night_20	$tmin \geq 20$
Water balance		
	rain_ge_eto	rain > eto
Photoperiod		
	photoperiod_range	min(photoperiod) - max(photoperiod)
Evaporative demand		
	vpd_range	vpd_tmin - vpd_tmax

Chilling was not calculated due to the variable nature of phenology by location.

5.1.9 Principal Component Analysis (PCA)

Principal component analysis (PCA) was used to explore relationships among locations and climatic variables and to identify the major environmental gradients influencing table grape production systems (Jolliffe, 1990, 2002). Analyses were conducted using functions available in base R (**?**).

Prior to analysis, all variables were centred and scaled to unit variance to account for differences in measurement units and magnitudes. The climatic attributes included in the PCA were selected on the basis of their likely physiological relevance to grapevine growth, productivity and adaptation.

Variable	Physiological interpretation
hot_35	Frequency of heat stress events
cold_night_le7	Exposure to cold nights
warm_night_20	Night-time respiratory demand
dtr_mean	Daily temperature amplitude
rad_sum	Annual radiation supply
eto_sum	Atmospheric evaporative demand
rain_sum	Water supply
vpd_tmin_mean	Night-time atmospheric demand
vpd_tmax_mean	Daytime atmospheric demand
photoperiod_range	Annual seasonality

The first two principal components explained 84% of the total variation among locations (Table 5.2), indicating that the climatic variation relevant to grapevine production can be represented adequately in two dimensions. The first principal component accounted for 54% of the total variance, while the second explained a further 30%. Table 5.2 summarises the contribution of each principal component to the overall variance structure of the dataset.

Table 5.2: Cumulative fraction of variance explained by principal components.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Standard deviation	2.33	1.73	0.78	0.67	0.50	0.34	0.29	0.17	0.13	0.11
Fraction of variance	0.54	0.30	0.06	0.05	0.03	0.01	0.01	0.00	0.00	0.00
Cumulative variance	0.54	0.84	0.90	0.95	0.97	0.99	0.99	1.00	1.00	1.00

Figure 5.1 shows the correlation structure among climatic variables included in the PCA. Several variables are strongly correlated, reflecting the underlying climatic gradients associated with latitude and aridity. The PCA was therefore used to derive a reduced set of orthogonal variables that summarised the major dimensions of climatic variation.

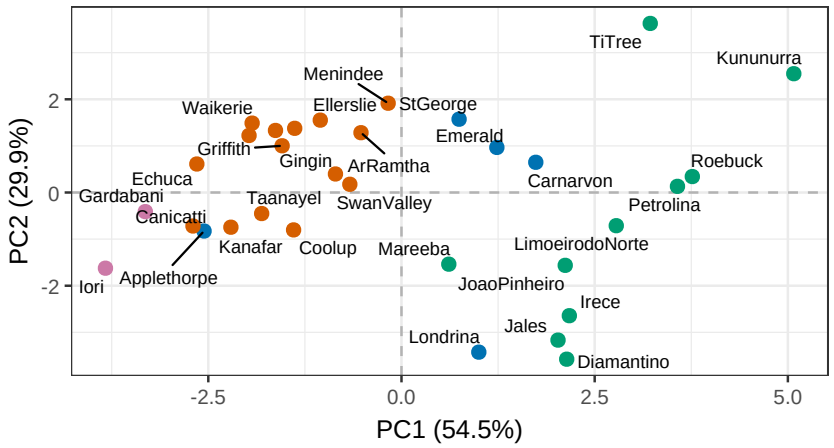


Figure 5.2: PCA analysis with the sites identified by their latitudinal location. Climate groups: ● Tropical, ● Subtropical, ● Mediterranean, and ● Temperate.

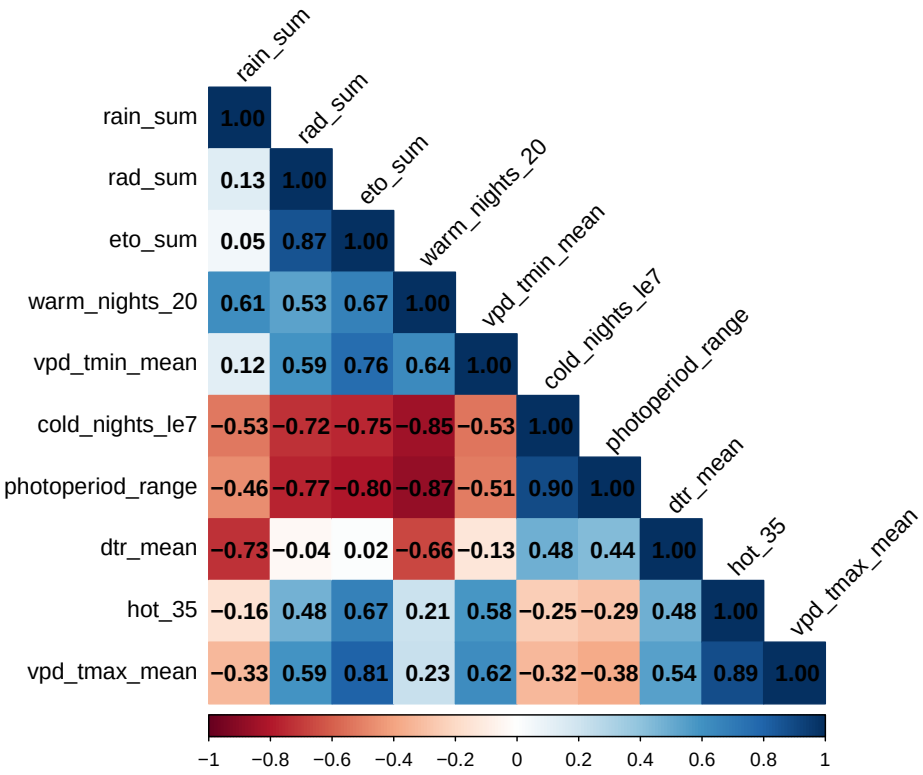


Figure 5.1: Correlation matrix of the variables included in Principal Component Analysis (PCA). All values are the mean of 26 years of the sum or mean of daily data. abb. rain_sum = annual rainfall, rad_sum = total solar radiation per year, eto_sum = annual evapotranspiration, warm_nights_20 = the sum of the count of nights in which Tmin was > 20°C

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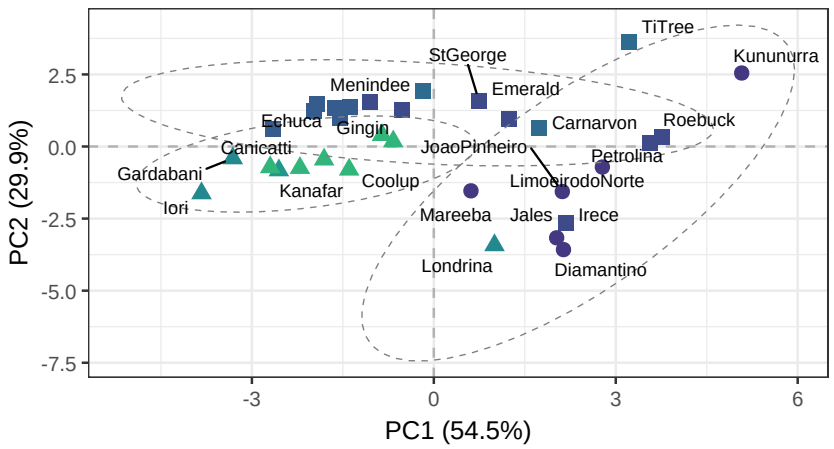


Figure 5.3: PCA analysis with the sites identified by their Köppen Geiger climate class:

- **Aw** Tropical Savannah, dry winter
- **Bsh** Dry, semi–arid, hot
- **Bsk** Dry, semi–arid, cold
- **Bwh** Dry, arid desert, hot
- **Bwk** Dry, arid desert, cold
- **Cfb** Temperate, no dry season, warm summer
- **Csa** Temperate, dry summer, hot summer

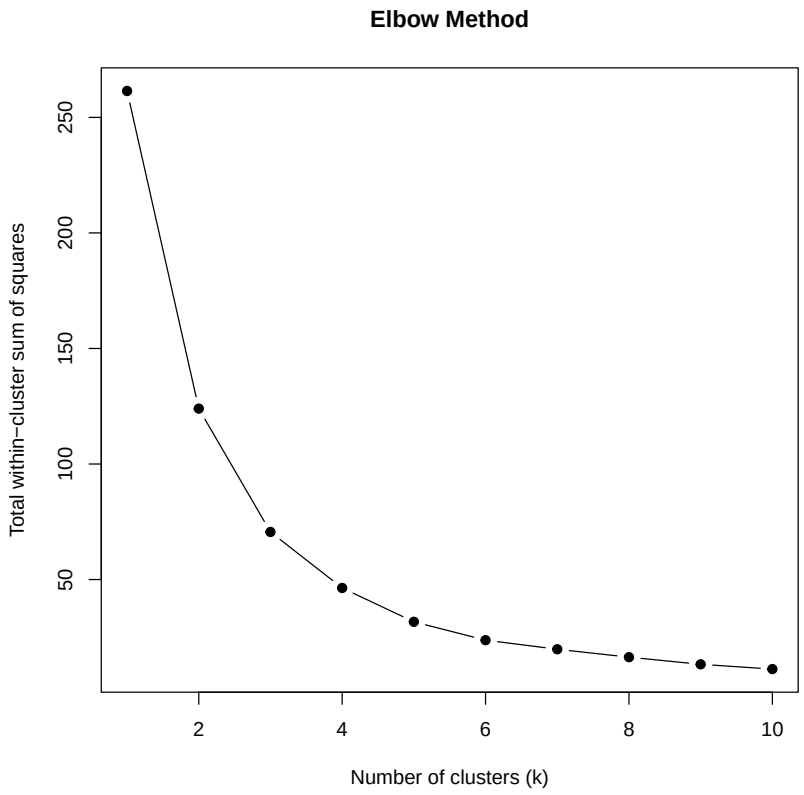


Figure 5.4: Elbow analysis assessment of the progressive benefit of adding clusters in the range 2 to 10.

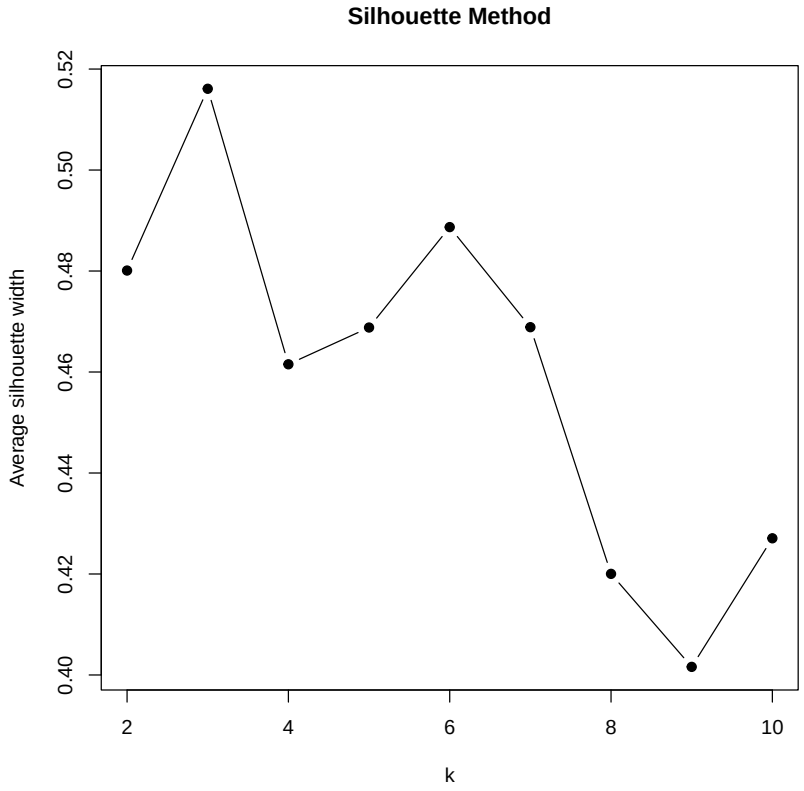


Figure 5.5: Silhouette assessment of the variance explained by settng cluster number in the range 2 to 10.

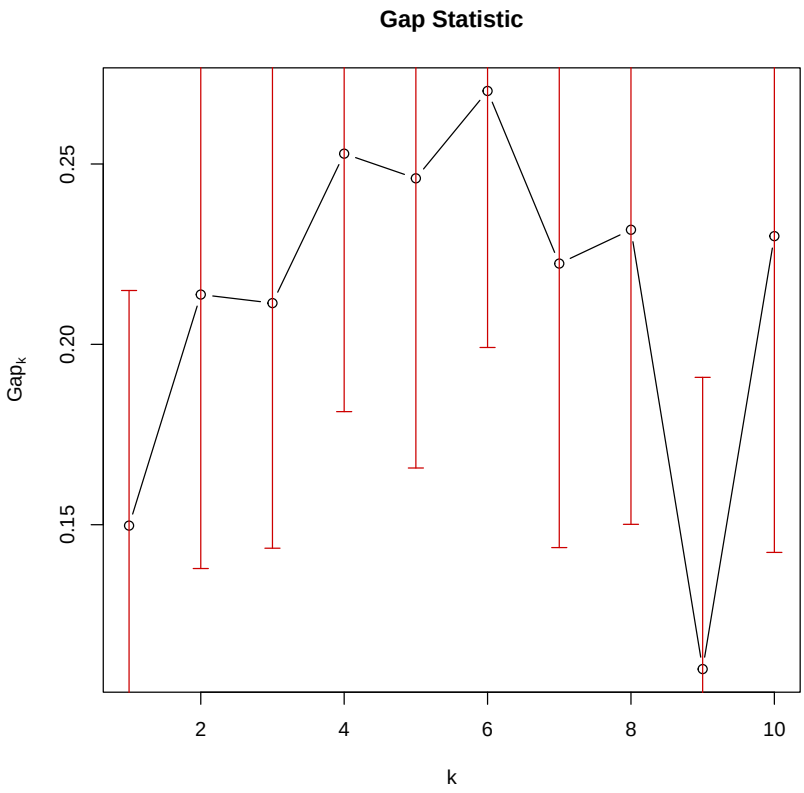


Figure 5.6: Gap analysis of the scores for various cluster numbers for the PCA scores.

The process used to aggregate locations into climatic groups is summarised in Figures 2.10, 5.2, 5.3 and 2.6. Figure 2.10 and Table 5.3 provide the core of the analysis. The PCA biplot represents the position of each of the 32 locations within a reduced two-dimensional climatic space derived from the ten environmental variables considered.

The first principal component (PC1) is dominant, accounting for 54% of the total variance (Table 5.2). It primarily represents a temperature and aridity gradient that broadly corresponds with latitude. Sites positioned to the left of the ordination tend to exhibit low photoperiod variation, warm nights and high evapotranspiration. Sites positioned to the right are characterised by larger day–night temperature ranges, greater seasonal variation, more frequent extreme heat events and higher vapour pressure deficits. The second component (PC2) accounts for a further 30% of the variance and is associated principally with gradients in heat load and moisture availability, particularly rainfall.

Figure 5.2 shows the same ordination with locations coloured according to conventional climatic zones. The resulting pattern demonstrates that locations do not form distinct groups based solely on latitude. Subtropical sites occur across much of the ordination space and Emerald is largely isolated from other members of that category. Classification according to Köppen–Geiger climate class (Figure 5.3) provides only limited improvement. These observations suggest that the environmental conditions relevant to grapevine productivity are more complex than can be represented by latitude or climate class alone.

Consequently, the locations were grouped according to multivariate climatic similarity rather than geographic designation (Figure 2.6). Although the clustering diagnostics identified three principal groups, a six-cluster solution was adopted because it represented a structured subdivision of the larger groups rather than statistical overpartitioning. The hierarchical relationship between the three- and six-cluster solutions suggests that broad climatic modes can be further resolved into functionally distinct environments. Importantly, this higher-resolution classification separated sites that appeared anomalous under conventional geographic classifications. For example, Köppen–Geiger classification associated Applethorpe with Kanafar, while Sunraysia was distinguished from neighbouring Riverland locations despite their apparent geographic similarity. The correlation structure among climatic variables is illustrated in Figure 5.1. Strong associations are evident among several variables and reflect common climatic gradients. For example, the incidence of cold nights is strongly negatively correlated

with both warm nights ($r = -0.85$) and photoperiod range ($r = -0.87$). Conversely, annual evapotranspiration is strongly positively correlated with annual solar radiation ($r = +0.87$). These relationships explain the substantial reduction in dimensionality achieved by the PCA.

The statistical clustering provides a coherent climatic interpretation of the sites. Petrolina and Roebuck, for example, are grouped within the 'Seasonal, Non-Dormant' category (Table 2.2). These locations share high annual maximum temperatures, elevated minimum temperatures, high evapotranspiration demand and among the highest vapour pressure deficits observed in the dataset. In contrast, St George is grouped with the principal Murray Valley production regions, possibly reflecting the moderating influence of elevation (Table 2.2). Coolup and Applethorpe are associated with the Mediterranean group and thus occupy climatic environments most similar to those within the natural distribution of *Vitis vinifera*.

This classification forms the basis for all subsequent comparative analyses of climate, productivity and adaptation among locations.

Table 5.3: Principal component loadings for latitude based climate metrics. The fraction of variance accounted for by PC1 and PC2 was 77.8% while PC3 brought that total to 88.8%.

Variable	PC1	PC2
Hot days $\geq 35°C$	0.24	0.39
Cold nights $\leq 7°C$	-0.38	0.19
Warm nights $\geq 20°C$	0.36	-0.26
Diurnal range	-0.11	0.54
Radiation (annual)	0.36	0.09
ETo (annual)	0.40	0.16
Rainfall (annual)	0.15	-0.45
vpd_tmin_mean	0.34	0.10
vpd_tmax_mean	0.27	0.43
Photoperiod range	-0.39	0.15

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Chapter 6

Appendix

6.1 R scripts

Note: Once run each script can be run independently.

However, should that result in saving a modified table, then any subsequent script requiring that table should also be re-run.

6.1.1 Current Scripts and supporting files

The scripts are available from the author.

config/config_au.txt	- repository of file paths and key variables.
config/variable_lookup.csv	
geodata/… *Global Koeppen Geiger map files*	
scripts/R	
common.R	- called within main body scripts
	- function for reading the config file
	- function for checking whether to read or read and write
runme_au.R	- not implemented but scripts organised to enable running as a 'pipe'
timebase.R	- phenology by site: incomplete
varmap.R	- lookup column name relationships for individual packages
	- called from within main body scripts if required.
AU1_read_sites.R	- Requires: <*config/config_au>; <R/common.R>; <R/varmap.R>
	- Filters sites from original excel file,
	- selecting google map point values: lat, lon, elev.
	- Tables: cfg; sites
	- Output: <data_working/sites_filtered.csv>
AU2_get_silo_daily.R	- Downloads selected climate variables from the SILO database
	- appends to sites tables
	- Tables: silo_raw; silo_std
	- Output: <data_working/silo_std_csv>;
	<data_working/silo_raw_csv>
AU3_get_other_sites.R	- Uses the ERA5 public data source
	- Downloads key daily data and calculates values missing from hourly data:rh_tmin, rh_tmax
	- Tables: era5_std
	- Output: <data_working/era5_std_csv>
AU4_combine_site_data.R	- Arranges tables from the ERA5 database to match those from SILO
	Calculates VP and VPD in a consistent fashion for all sites, ERA5 and SILO
	- Tables: met_std
	- Output: <data_working/met_std.csv>
AU4_supp_add_parameters.R	- Enables additional parameters to be added to the whole database from ERA5: here atmospheric pressure at ground level
	- Input <working_data/sites_filtered.csv>; <era5_std.csv>
	- Updated <era5_std.csv>
AU5a_photoperiod.R	- Global lookup data for photoperiod at 0.1° resolution
	Run once only
	- Tables: photo – lookup
	<data/photoperiod_lookup_lat0.1deg.csv>
AU5b_photoperiod.R	- Extracts and appends photoperiod to site data
	- Requires: met_std
	- Tables: met_std
	- <output/photoperiod_by_day.csv>
	<data_working/met_std.csv>
	- i.e. overwrites previous file

Note: Mapping scripts exclude international sites from all tables and exclude met_std	
AU6a_ausMap.R	- Adds geographic regions. Simple map with sites and latitude markers - outputs exclude non–AU sites - To do: Add labels to sites - Requires: sites, rnaturalearth, rnaturalearthdata - Tables: sites_meta, sites_sf tables - Output: <data_working/sites_meta.csv>, <figs/ausMap_regions.pdf>, <data_working/sites_meta_au.csv>, <data_working/sites_sf_au>
AU6b_KG_map.R	- maps minor kg sites as underlay: NEEDS REVISION OF ORDER - Requires: <geoData/KG/1991_2020/koppen_geiger_0p00833333.tif>; $sites_sf - Output: Appends KG classification to sites based on 10 km buffer <data_working/sites_meta_au.csv> <figs/KG_minor_map.pdf>
AU6c_AuBR_map.R	- Underlay map of the major biodiversity regions of Aus Append classification to sites - Output: <figs/ausBioregions.pdf>; "cfg$sites_meta_file"
AU6d_vegMap_au.R, *AU6d_vegMap_au_pt2.R*	- Underlay map of Australian vegetation as index of site. - Prepares data for mapping with QGIS - Output: <output/sites_with_veg.csv> <figs/AusVegDraft1.pdf>, <AusVegDraft1.png>
Note: Add back the non–Au sites and their classifications	
AU6e_update_sites_intl.R	- Add to core sites table the classifications missing from the international sites. - Requires: "cfg$filtered_sites_file; "cfg$sites_sf_file"; "cfg$sites_meta_file" - Output: data_working/all_sites_meta.csv
AU7a_min_metrics.R	- Define additional variables, hot days ... - Requires: "met_std_file"; - Output: <results/minimal_metrics.csv>
AU7b_metrics_lat_PCA.R	- PCA and k–means cluster analysis - Note missing vegetation? Updates all_sites_meta with cluster groups - Requires: sites, sites_sf, sites_meta - Output: p1, <figs/PCA_kg.pdf> and <PCA_kmeans>, <figs/PCA_loadings.pdf, extended metrics>
AU7c_metrics_kg_PCA.R	- Repeat of 7b but labelled by Köoppen Geiger <figs/PCA_1KG.pdf>
AU7d_hydrocoolingIndex.R	- added to AU7e - estimates of potential gains from field scale hydrocooling