

Review



A Review of Factors to Consider for Permanent Cordon Establishment and Maintenance

Patrick O'Brien¹, Roberta De Bei¹, Mark Sosnowski^{1,2} and Cassandra Collins^{1,3,*}

- ¹ Waite Research Institute, School of Agriculture, Food and Wine, The University of Adelaide, PMB 1, Glen Osmond, SA 5064, Australia; patrick.obrien@adelaide.edu.au (P.O.);
- roberta.debei@adelaide.edu.au (R.D.B.); mark.sosnowski@sa.gov.au (M.S.)
- South Australian Research and Development Institute, GPO Box 397, Adelaide, SA 5001, Australia
- ³ ARC Industrial Transformation Training Centre for Innovative Wine Production, Waite Research Institute, PMB 1, Glen Osmond, SA 5064, Australia
- * Correspondence: cassandra.collins@adelaide.edu.au

Abstract: Decisions made during the establishment and reworking of permanent cordon arms may have long-term consequences on vineyard health and longevity. This review aims to summarise several of the important considerations that must be taken into account during cordon establishment and maintenance. Commonly practiced cordon training techniques such as wrapping developing arms tightly around the cordon wire may result in a constriction of the vascular system, becoming worse over time and disrupting the normal flow of water and nutrients. Studies have shown that other factors of cordon decline such as the onset of vascular diseases may be influenced by preexisting stress conditions. Such conditions could be further exacerbated by water and heat stress events, an important consideration as these scenarios become more common under the influence of climate change. Vineyard sustainability may be improved by adopting cordon training techniques which promote long-term vitality and avoid a reduction in vine defence response and the costly, premature reworking of vines.

Keywords: grapevine; constriction; water movement; trunk disease; training; decline; drought resilience

1. Introduction

Grapevines (Vitis vinifera L.) are woody perennial plants, which under the right conditions can sustain impressive longevity, producing fruit over many growing seasons [1]. In extreme examples, their lifespan may have the potential to exceed 400 years, as is the case of the Old Vine from Lent (Maribor, Slovenia), regarded as the oldest living example of cultivated grapevine in the world [2]. Typically, older vineyards are more highly coveted than their younger counterparts, particularly with red cultivars, with their fruit and resultant wine being perceived as having higher potential quality [3,4]. It is not uncommon for commercial vineyards to remain productive for 50–60 years, and in long established regions, commercial vineyards may be found with average vine ages of well over 100 years. It is becoming increasingly rarer, however, to observe vines of this age around the world, and it is not unusual to see vineyards undergo major reworking or replanting after only a few decades, either to be replaced with other cultivars or due to a decline in production relative to crop value [5]. A number of factors may, on their own or in a cumulative manner, contribute to a vineyard's eventual decline in yield and economic viability including nematodes [6], trunk diseases [7–9], viruses [10,11], phytoplasmas [12], and other problems arising from poor management decisions such as improper selection of rootstock, poor pruning practices, mechanical damage, nutrient and irrigation deficiencies, lack of weed control, and compaction of the soil [13] (Figure 1). These issues are further complicated by climate change, the impacts of which are well documented and include increases in global temperature, CO₂ concentration, and solar radiation, as well as extreme



Citation: O'Brien, P.; De Bei, R.; Sosnowski, M.; Collins, C. A Review of Factors to Consider for Permanent Cordon Establishment and Maintenance. *Agronomy* **2021**, *11*, 1811. https://doi.org/10.3390/ agronomy11091811

Academic Editor: J. Antonio Cortinas Rguez

Received: 3 August 2021 Accepted: 8 September 2021 Published: 9 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).



changes in weather patterns and increased frequency of drought conditions and water scarcity [14–17].

Figure 1. Factors which many have an influence on vineyard longevity. (**a**) Loss of spur positions as a result of mechanical damage, improper pruning, or dieback; (**b**) strangulation of the cordon; (**c**) insufficient carbohydrate reserve storage in perennial organs, or reduced functionality from vascular disease, virus infection, phytoplasma infection, or improper selection of rootstock; (**d**) poor soil water content, or irrigation mismanagement; (**e**) soil compaction; (**f**) soil pathogens including nematodes; (**g**) nutrient mismanagement, or poor soil microbial activity; (**h**) inadequate weed control; (**i**) mismanagement of cover crops and/or insect populations; (**j**) seasonal impacts such as frost damage and major heat events; (**k**) changing climate and weather patterns.

Other management decisions made during the establishment or reworking of vineyards may have lasting consequences on vineyard health and longevity as well. In Australia, and in many grape-growing regions around the world, it is a common practice for canes to be wrapped tightly around the cordon wire during the establishment of permanent cordon arms. It stands to reason that this wrapping may cause a constriction of the vine's vascular system, becoming worse over time and disrupting the flow of water and nutrients [18]. This is especially apparent in older vineyards, where the wire is often visibly embedded within the wood of the cordon and signs of decline and dead arm symptoms are frequently observed. It is possible that the stress resulting from the constriction of the vines vasculature may reduce the vines natural ability to deal with external factors such as the onset of vascular diseases. This condition could also be further exacerbated by water and heat stress events, an issue of major concern as these scenarios become more and more common under the influence of global warming. While there are many different factors which may play a contributing role in the overall health and longevity of a vineyard, this review will focus primarily on those most likely to directly impact the vitality of permanent cordons arms, as well as the best practices for their establishment and maintenance.

2. Physiology of the Grapevine

2.1. Water and Nutrient Transport

Grapevines, like all vascular plants, require water to grow and thrive [19]. The movement of this water throughout the vine, along with essential mineral nutrients, sugars, and amino acids, is achieved via the vascular system [20]. Along with providing this principal function, the vascular system also provides the vine with mechanical support, important as grapevines in their natural state are climbing plants. Water is transported in the form of sap, the ascent of which is explained by the cohesion-tension theory whereby the evaporation of water molecules at the leaf surface during transpiration pulls water from the soil into the roots and through the xylem conduits towards the leaves [21,22]. This process uses no metabolic energy; rather the movement of water is driven by capillary forces, and the xylem conduits that serve to carry a network of broken and more importantly unbroken "threads" of sap are composed of dead cell walls [23,24]. The water within the xylem conduits is constantly under tension (i.e., the xylem pressure potential is negative), and this tension increases with a reduction in soil moisture or increase in transpiration rate [25]. It is upon this concept that the soil-plant-atmosphere continuum (SPAC) model is based [26], as well as the Ohm's law analogy, where water flux through the various parts of the SPAC is treated as a catenary process, comparable to the current in an electric circuit composed of a series of conductances (or inversely, resistances) [27]. Using this analogy, the flux of water through a part of the vine can be thought of as being proportional to the product of the hydraulic conductance of that region and the water potential drop across said region [27]. Other significant components of the vascular system include the phloem, which is important in the transport of water and nutrients and plays a major role in inter-organ communication, and meristematic tissues, which are regions of unspecialised cells contributing to vital activities including cell multiplication, secretion, photosynthesis, and storage [28].

2.2. Xylem Morphology

Healthy cordons require healthy vascular systems for the translocation of water and other important substances. It has been demonstrated that xylem morphology is impacted by water availability [29,30], and hydraulic properties of old wood are different from those of young shoots, as vessel length and diameter are correlated with stem diameter and mature trunks and limbs tend to have longer, wider vessels compared to younger stems [31–33]. Additionally, the ratio between the width of the xylem and total stem diameter is greater in mature stems [34]. Xylem conductivity is determined by the structure and size of vessels [27,35] as well as their efficiency, which may be affected by the presence of embolisms (air-filled conduits that are not available for water conduction) [29,36]. Along with non-living tracheary elements (vessels and tracheids interconnected by lateral pits), the secondary xylem contains other cell types including fibres and living parenchyma cells, the latter of which are in contact and communication with xylem conduits [27,37]. Although non-living cells cannot respond to wounding or parasite entry, living cells may respond by excreting gels, lignin precursors, and other substances, or by forming tyloses (extensions of adjacent parenchyma cells into vessel lumens) [38,39]. Such responses may be triggered by several factors including frost, flooding, wounding, leaf abscission, and infection by different pathogens, and function as a xylem-sealing mechanism, obstructing the conduction of water through the affected xylem [40]. These vascular occlusions serve an important function in wound sealing and reducing the spread of pathogens in the xylem [38,41,42]. Working with Chardonnay, Sun et al. [37] reported that the type of occlusion induced after wounding was dependent on the season in which wounds were inflicted, with tylose formation resulting in permanent xylem obstruction occurring predominantly in the summer and reversible gel formation occurring predominantly in the winter. This study also showed that a higher fraction of vessels developed occlusions in summer and autumn (over 80%) than in winter and spring (about 60%). Of particular interest is whether the physical stress of tightly wrapping developing cordon arms around the cordon wire could induce a wound response resulting in the restriction of the normal flow of water

and nutrients along the cordon. Such interruptions to water transport, particularly in the context of climate change, could have a drastic impact on cordon health and productivity.

2.3. Phloem Morphology

While xylematic flow is driven by a tensional gradient along a series of dead cells, in contrast, the phloematic conduit is comprised of a series of living cells forming a sieve tube system [43]. A wide variety of substances are transported via the phloem to distant organs, including sugars, amino acids, micronutrients, lipids, hormones, proteins, and RNAs [28]. Some of these materials serve an important role as informational or signalling molecules [44]. The phloem of *Vitis vinifera* is somewhat atypical compared to most other plant species in that it has an unusually long life, with its sieve tubes functioning for more than one year, becoming inactive during the winter and resuming activity in the spring [45]. This reversible inactivity begins with the sieve tubes developing a provisional callus before the onset of winter dormancy, and terminates in the spring with the sieve tubes acquiring the same characteristics of active elements as when first differentiated from the cambium [45]. Once the cambium is activated during the early stages of the growing season, it begins to generate new phloematic tissues that will mature by the end of the season, when the phloem of the previous year will begin a process of loss of functionality and obliteration [46]. Occlusion of dead, non-conducting sieve elements may occur from outgrowths of contiguous parenchyma cells known as tylosoids (tylose-like protrusions which do not grow through pits in secondary walls) [47]. Such protrusions may invade the lumina of inactive sieve elements or simply push the sieve element wall to one side, resulting in the collapse of the sieve element [28]. The growing season begins and ends with one ring of functional phloem, with the activity of the phloematic tissues generated during two consecutive growing seasons overlapping temporarily mid-season [45,46]. Early spring vegetative growth is driven by the translocation of carbohydrate reserves from perennial organs [48–50], which become available for budburst with the generation of auxins, degradation of callose, and reactivation of the phloem [51].

2.4. Effects of Water Stress

Although some growers utilise deficit irrigation methods to impose water constraint as a means of improving fruit quality [52,53], there remains a question as to whether this practice may be detrimental to vine longevity owing to the stress imposed. Under the effects of water stress, vines show changes in water flow rate resulting from modifications of the conductivity components of the transpiration pathway (root, shoot and stomata) [29]. It has been reported that water stress affects shoot conductivity by inducing embolism in the xylem vessels [29,36,54,55]. It has also been demonstrated that water deficits during the growing season can inhibit vine vegetative growth and photosynthesis [54,56–58] as well as having a negative effect on yield and fruit/wine composition [59–62]. Such deficits affect the source-sink balance of the vine [63], and may therefore affect productivity both in the current growing season as well as in following years given that early spring shoot growth is supported by and reliant on reserves [48–50]. In their study on Malbec, Dayer et al. [56] found that severe water stress reduced trunk starch concentration without having an effect on the concentration of total non-structural carbohydrates. This is in agreement with previous studies which found that the seasonal impacts of water deficit could potentially inhibit starch accumulation in peach trees [64] and grapevines [65]. It is therefore reasonable to hypothesise that water stress symptoms caused or exacerbated by the constrictive effects of wrapping developing arms tightly around the cordon wire could lead to a reduction in carbohydrate reserves that could have a long-term impact, hindering growth in future seasons. Likewise any reduction in cordon volume occurring as a result of constriction could directly affect the vine's capacity to overwinter carbohydrates as the perennial structures of the vine including the roots, trunk, and cordon are the major storage organs for carbohydrates [48].

2.5. Impact of Cordon Health on Reproduction and Vine Balance

Another issue of concern is whether cordon constriction could have an impact on fruitfulness, measured as the number of inflorescences per node after budburst, or during para-dormancy as the number of inflorescence primordia (IP) within the compound bud with the potential to develop into inflorescences the following season [66]. Inflorescence development and shoot growth rely on current season photosynthesis, as well as the translocation of previous season reserves, and carbohydrates are supplied to developing shoots and inflorescences via remobilisation from perennial structures [48,67]. Vegetative and reproductive growth occur simultaneously, and as such competition for carbohydrate reserves may exist between vegetative and reproductive structures under stress conditions when resources are not sufficient to support potential growth rates [58,68,69]. Sustainable viticulture therefore requires a balanced vineyard that via canopy photosynthesis during the growing season is able to provide enough carbohydrates to ripen the target fruit load and support IP development as well as replenish sufficient reserves in the perennial organs to enable budburst and support initial spring shoot growth in the following season [56,70]. In a study on Shiraz, the number of bunches per shoot and berries per bunch were found to be correlated with water and nitrogen availability during flowering the previous season [71]. If the primary bud dies during initiation due to a physiological disorder known as primary bud necrosis (PBN), then secondary buds, which are less fruitful and form smaller bunches, may grow in compensation for its loss [72]. Given studies have found that the incidence of PBN may be influenced by reduced bud carbohydrate levels [73] and water deficit [74], it is possible that any interruption in the vasculature of the cordon induced by wrapping may have an influence on the incidence of PBN as well. IP number and size are also likely to be influenced by such an interruption regardless of whether the primary bud becomes necrotic.

3. Cordon Establishment and Maintenance

3.1. Selection of Training System

One of the most important decisions during the establishment of a new vineyard is the choice of training system. This decision may be based on a number of factors including cultivar, soil, climate, accessibility of mechanical equipment, demand for regulation of vegetative vigour, cost, and consideration of historic regional management practices [75,76]. Planting choices including rootstocks, trellis and vine spacing, and the heights and thickness of wires can affect productivity during vine establishment and also in the long-term. An important distinction regarding vines that are hedgerow trained is the presence or absence of a permanent cordon. Regardless of other decisions of training system (i.e., unilateral vs. bilateral cordon, divided vs. non-divided canopy, vertically shoot positioned vs. sprawl, etc.), a choice must be made as to whether permanent cordons or canes will be used to supply the nodes from which the fruit-bearing shoots will grow each season. In the case of cane pruning, 1–8 canes (commonly two) of reasonable length from the previous season are selected and retained each year, usually from the crown of the vine and as such no permanent arms are required. These canes are then trained and secured to the cordon wire(s), often wrapped around the cordon wire itself, or brought over top of another parallel wire and back down to the cordon wire to form an arch. Studies have indicated that the selection of thicker canes may be beneficial in increasing yield and profitability. In a study on Sauvignon blanc over two growing seasons, Eltom et al. [77] determined that average inflorescence number per shoot and the proportion of inflorescences having an outer arm with flowers increased in relation with an increase in cane diameter. Cane microclimate is an important consideration in this instance as inflorescence number per bud is influenced by environmental conditions (primarily light and temperature) during the initiation of inflorescence primordia [78]. While cane pruning has the advantage of maintaining the most fruitful nodes [79], it is more expensive than spur pruning and a tendency towards apical dominance may result in uneven budburst [80]. Carbohydrate reserves may also potentially be impacted as 2-year-old wood may be removed [81]. In

contrast, spur pruning normally involves the retention of spurs of 2–3 nodes located along a permanent cordon, with wood no older than one growing season being removed in the case of healthy vines. Along with cheaper pruning costs, this system has the advantage of having a higher capacity for reserve storage and often more uniform shoot growth [82]. It is also more suitable to mechanisation than cane pruning, and may significantly reduce yearly labour demand, even if hand harvesting and pruning are employed [83]. A mechanical pre-pruning followed by a light manual pruning is a popular technique among growers, that along with reducing labour costs, may help to maintain cordon vitality over time by promoting proper pruning practices. The ease of operation afforded by such a strategy could, for example, encourage the careful selection of nodes and consideration of the types of cuts being made. Along with increased susceptibility to longevity related issues such as dieback, other important considerations regarding the use of permanent cordons include the selection of cultivars suitable for their basal fertility, as well as the use of canopy management practices which optimise the positioning of foliage and bunches for mechanisation.

3.2. Wrapping Canes Tightly around the Cordon Wire

In many wine-producing countries, it is a common practice for canes to be wrapped tightly around the cordon wire during the establishment of permanent cordon arms for several reasons. Wrapping the canes around the cordon wire has the inherent advantage of providing the developing arms with additional support, reducing the risk of rolling and mitigating the need for foliage wires. This added support is especially appreciated in heavily mechanised regions such as Australia, where the stability of the canopy is an important factor in regard to limiting mechanical damage. While some growers have begun to wrap canes more loosely around the cordon wire out of concern for strangulation, it is unclear whether or not this practice is enough to totally eliminate the possibility of the wire becoming embedded within the wood of the cordon and eventually affecting productivity. Other methods including placing the canes on top of the wire and securing them in place in three or four positions on each arm [18], or utilising a coiled wire through which the canes may be trained [84], can be more costly and time consuming by comparison. Having the cordon trained on top of the cordon wire also requires the presence of at least one foliage wire, as in the absence of any support for developing shoots to latch on to, arms positioned in this fashion have a tendency to roll under the influence of their own weight [18]. This can disrupt the selection and formation of permanent spur positions and potentially overexpose any fruit that may be present. The risk of rolling is also related to cordon length, with longer cordons having a greater susceptibility.

It has been hypothesised that wrapping the cordon tightly around the cordon wire may cause a constriction of the vascular system, becoming worse over time and disrupting the normal flow of water and nutrients through cordon arms [18,85]. This stress may in turn contribute to a decline in productivity and the occurrence of dead arm symptoms, either on its own or in combination with other factors. While little research has been conducted on grapevines in this regard, it has been reported that constriction applied via plastic straps on olive trees led to a reduction in vegetative growth and canopy volume compared to control trees, as well as a reduction in yield for low vigour cultivars [86]. This reduction in vegetative growth corresponded to lower stem water potential in constricted trees, likely as a result of reduced xylem girth growth caused by the plastic strap at the constriction point [87]. A similar reduction in vigour was observed after girdling (removing a thin strip of the outer stem layer, i.e., cambium and phloem) in various orchard trees [87–90], especially when performed early in the season. Such an interruption to the phloem prevents the downward flow of sugars and other organic compounds, with extra damage or even death resulting if the cut is deep enough to damage the xylem or is too slow to heal [91]. Girdling is commonly used in table grape production to increase yield [92], and is sometimes utilised in winegrape production to promote sugar and anthocyanin accumulation [93]. Working with Kyoho grapevines, Li et al. [93] demonstrated that

prolonged disconnection of the phloem after girdling significantly suppressed the length of fruiting shoots and the number of leaves per shoot on girdled arms, possibly due to a disruption of the accumulation of carbohydrate reserves in the trunk and roots. Similar results were obtained by Eltom et al. [94] who, working with Sauvignon blanc, determined that cane girdling before budburst restricted carbohydrate availability and reduced shoot growth rate and internode number. Based on these results it seems probable that any disruption to the vines vasculature imposed by constriction could inhibit carbohydrate accumulation in the perennial organs, negatively affecting growth and productivity in the following seasons. Investigating the effect of tight wrapping on the developing arms of Shiraz, Caravia [85] reported pruning mass to be around 20% higher in non-wrapped vines after a single season, suggesting more favourable conditions for growth. This was further supported by measurements of arm transversal area (ATA) which was found to be significantly higher in the distal portion of non-wrapped arms compared to wrapped arms. Additionally, significantly higher concentrations of soluble sugar were observed at the distal portion of non-wrapped arms during dormancy and there was a trend (though not significant) of higher trunk starch concentration in non-wrapped vines. While the reduced vegetative growth observed in the wrapped cordons and the lower concentration of sugars observed in the distal portion of wrapped arms seem to suggest that constriction may have had a negative effect on xylematic flow, the same cannot necessarily be said about phloematic flow. Considering that an interruption to the phloem would be likely to disrupt the translocation of carbohydrates to perennial structures for overwintering, one would expect that the concentration of sugars observed in the distal portion of arms during dormancy would be higher in the case of the tightly wrapped arms had there been such an interruption.

3.3. Establishment of Cordon Arms

When establishing permanent cordon arms during the development or reworking of a vineyard, canes are selected based on several factors including their vigour, health, and perhaps most importantly their proximity to the cordon wire. This selection is important as it has a permanent impact on the vine's canopy architecture, and in the case of bilateral cordons, the formation of a "v-zone" of appropriate size at the crown of the vine helps to regulate canopy density, improving light and wind penetration and reducing the risk of future foliar disease pressure. In certain scenarios, a unilateral cordon may be preferable over a bilateral cordon when accounting for factors such as vigour and intra-row vine spacing. The length of cordon arms is often decided based on this spacing, with the distal ends of the arms of two adjacent vines ending in close proximity to each other. Perhaps unsurprisingly, as any gaps along the cordon wire without the presence of productive cordon equates to a loss in potential profit. As such, common practice involves cutting canes intended as future bilateral cordon arms to a length equal to about half the distance between the trunks during establishment, effectively leaving them as long as possible. While this method has the advantage of getting the entirety of the desired length of the new arm into position right away, evidence suggests that it may not always be the best approach. The capacity of newly established arms to grow and develop new shoots, as is the case with all parts of the vine is based on vigour [81]. When low vigour-canes with a small diameter are selected for the establishment of new cordons, possibly by necessity due to a lack of better options as the case may be, a length adjustment based on the apparent vigour of the canes may be an advisable consideration [95]. Canes of small diameter may not have the vigour needed to support uniform budburst and growth of new shoots, especially in the case of the buds located in the middle of the canes [96]. By adjusting the length of the canes intended as new arms based on their apparent vigour (Figure 2), less buds are retained, encouraging their successful growth and the development of shoots that are of greater diameter and are better suited for selection as permanent spur positions [81,97].



Figure 2. Length adjustment of low-vigour canes selected as permanent cordon arms. (**a**) Both canes selected as permanent cordon arms were deemed suitably high vigour and did not receive a length adjustment; (**b**) one cane selected as a permanent cordon arm was deemed to have an apparent vigour too low to support uniform budburst and shoot growth and received a length adjustment based on its apparent vigour.

One of the shoots from the most distal portion of the developing arm, close to the cutting point, may then be selected and trained along the cordon wire horizontally during the growing season to extend the cordon arm to its final length. This process may require attention several times to secure the extension as it grows but the desired result is more numerous, healthier spur positions. Following the same logic, the removal of secondary shoots as well as those growing from locations deemed undesirable for permanent spur positions [97,98]. An early shoot thinning, performed when newly burst shoots are 5–10 cm, could help to combat the acrotonic tendency of the vine to send sap to the most distal nodes, improving uniformity in the length and diameter of shoots along the cordon [99].

3.4. Maintenance of Cordon Arms

A healthy permanent cordon may lose productivity simply as a result of decisions made during the spur pruning process. "Blinding" of spur positions (for example removing one node out of every two along the length of the cordon, or removing all of the nodes within the v-zone) is a process that is sometimes performed intentionally for the purpose of keeping productivity low or maintaining spatial separation between spurs [97]. This process is ideally performed on 1-year-old canes during establishment by scraping off undesired buds or early developing shoots. Spur positions may also be lost unintentionally, sometimes permanently, due to the overzealous actions of pruners with insufficient experience in selecting which spurs to retain each year. Likewise, any accidental nicking of the cordon or other wood older than 1-year-old, deep enough to damage the vasculature or illicit a wound response, or producing larger cuts than necessary, could be detrimental to vitality [95,100]. Cordon length is an important consideration in relation to vine vigour. Cordons of insufficient length may lack the spur positions required to provide an adequate framework for the substantial amount of vegetative growth observed in high-vigour situations. Likewise, excessively long cordons may be unable to support uniform budburst and growth, especially in low-vigour situations, leading to underdeveloped or missing spur positions [96]. Important pruning practices include limiting the number and size of clean cuts in order to help reduce the susceptibility of the cordon to fungal trunk disease infection, as well as avoiding pruning during wet conditions when spore inoculum is prevalent [101]. It has been suggested that training methods involving minimal pruning

show less esca disease effect than methods involving regular manual pruning [102], and techniques which concentrate pruning wounds on the crown of the vine should be avoided, particularly for cultivars sensitive to wood disease. Recent research has indicated that the total surface area of cuts on a cordon rather than the diameter of each cut is the more important factor in regard to incidence of Eutypa dieback [103]. Such wounds may expose the vascular system to the environment, dehydrating cells adjacent to cuts and producing desiccation cones [104], susceptible to colonisation by fungal pathogens [105,106]. It is also important to be cognizant of the proximity of the cutting point to retained buds when spur pruning, as necrosis will occur near the cutting point which must be allowed for with a desiccation zone. It is recommended to allow for a length between the cutting point and retained buds equal at a minimum to twice the diameter of the wood being pruned [97,107], so as not to compromise the vitality of the wood tissue in close proximity to the bud. A recent study by Faúndez-López et al. [104] has indicated that the area and depth of wood necrosis induced by pruning is influenced by the distance between the cutting point and the node, but not by the diameter of pruned spurs. Interestingly, this study also found that budburst and shoot development were not affected by the distance between nodes and pruning cuts. A new method being promoted by some practitioners involves retaining the top node position of each spur in a two-node spur system preferentially each year [108], allowing for a gradual increase in spur position height, purporting to reduce trunk disease incidence. This is in contrast to the classic and widely adopted method of retaining the bottom node each year, which has the benefit of limiting variation in cordon architecture and keeping the height of spur positions in closer proximity to the cordon. While both methods have their advantages, an issue that may arise with unchecked vertical or horizontal elongation of spur positions is an increase in the frequency of breakage via mechanical damage [109]. Shifting the vegetation further away from the cordon also inevitably results in an unavoidable progressive loss of leaf area, if the trimming/hedging point remains unchanged. Overly tall spur positions may, however, be brought back down to starting height periodically when necessary, with the use of a replacement cane originating in close proximity to the cordon [108]. One added benefit of tall spur positions is an increase in the volume of perennial wood, providing greater capacity for carbohydrate reserve storage. Increased spatial separation of the fruit zone from the cordon may also have positive implications on bunch microclimate and fruit and foliar disease pressure.

4. Vascular Diseases of Grapevine

4.1. Mechanism of Infection and Implicated Pathogens

Grapevine trunk diseases are caused by a range of phytopathogenic fungi and represent a serious challenge to viticulturists all over the world, having the capacity to drastically reduce vineyard productivity and cause significant loss of income [110]. In a study examining the impact of grapevine age on water status and productivity of Riesling, Bou Nader et al. [5] identified wood diseases as the main factor behind the decline of old vines, suggesting that their management is a key component in regard to improving vineyard longevity. Trunk disease pathogens associated with the decline and dieback of grapevines include species of the Diatrypaceae family, most prominently Eutypa lata [111,112], species of the Botryosphaeriaceae [113–115], Phomopsis spp. [116], various basidiomycete species [117], Phaeomoniella chlamydospora [118], Phaeoacremonium spp. and Cadophora spp. [119], among others. These pathogens infect the grapevine primarily through pruning wounds, with spores dispersed by wind and rain splash germinating in exposed xylem vessels upon contact and colonising woody tissue [120]. The same grapevine can by infected multiple times with one or more fungal pathogens, with different pathogens causing similar symptoms of decline, supporting the idea that trunk diseases may best be regarded as a complex of infections [121–123]. Occlusion of the xylem and phloem elements may occur in infected vines, along with wood decay, impairing the translocation of water and nutrients [124]. Visible symptoms of decline often do not develop until 10 or more years after planting and may include uneven periderm maturation, stunted shoots,

10 of 18

necrotic and marginally scorched or distorted leaves, reduced bunch size, uneven ripening, fruit wilting, and eventually vine death [125,126]. Studies have suggested that variations in the severity of symptoms from year to year may be more influenced by climatic factors such as rainfall and temperature than by vineyard practices [110,127].

Pierce's disease, also a vascular disease of the grapevine, is caused by the xylemlimited bacterium *Xylella fastidiosa* (Xf) and is transferred from vine to vine by sap-feeding insect vectors [128]. Expression of symptoms occur as a result of the systemic colonisation of the xylem by Xf and the progressive occlusion of xylem conduits. The disease is fatal to grapevines, as the development of tyloses, gels, and embolisms in xylem vessels cause vascular transport to become increasingly impaired, resulting in water deficits and their associated consequences [129,130]. Drought conditions and water shortage issues are becoming more and more common under the influence of global warming. Accordingly, such impediments to the movement of water and other substances through the vasculature of the cordon and other vine tissues, as well as their interaction with environmental conditions, are becoming of increasing concern.

4.2. Relationship between Stress and Disease Symptom Expression

Vines may be infected by fungal and bacterial pathogens without displaying any symptoms. Several studies have yielded results indicating that infected vines may be more likely to express symptoms when their health is compromised by stress. Water stress has been shown to exacerbate disease symptoms associated with Phaeomoniella chlamydospora (Pc), a pathogen implicated in esca and Petri disease [131,132]. Leaf water potentials were determined to be lower in infected Cabernet Sauvignon and Zinfandel vines when subjected to water stress, indicating that infection inhibited the ability of the vines to transport water. In a greenhouse trial, Ferreira et al. [133] observed that significantly more Chenin blanc vines inoculated with Pc exhibited dieback symptoms when subjected to water stress. Similarly, working with Müller-Thurgau and Riesling, Fischer and Kassemeyer [134] observed a greater number of symptomatic xylem vessels in vines infected with Pc when subjected to water stress. Investigating the effect of water and temperature stress on grapevines inoculated with Eutypa lata (Eutypa dieback), Sosnowski et al. [135] demonstrated that Red Grenache vines in pots subjected to a combination of extreme heat or cold plus low or high soil moisture displayed more severe foliar symptoms than those in moderate conditions; however, severe symptoms were not produced with either of these factors alone. In a subsequent water-deficit trial, the extent of colonisation of E. lata and Diplodia seriata (Botryosphaeria dieback) did not increase under water stress, with the progress of *E. lata* actually showing a reduction in water stressed vines [136]. Further examining the same vines and irrigation treatments, Oswald [137] reported that smaller xylem vessel area and narrower cane diameter were correlated with less colonisation of *E. lata* in the water stressed vines, contradicting the theory that restricting vascular tissue might lead to increased progression of Eutypa dieback. Additionally, Pouzoulet et al. [138] reported that increased xylem vessel diameter was correlated with greater susceptibility to Pc, due to less efficient vessel compartmentalisation.

Pierce's disease produces symptoms which have been found to correlate with low leaf water potential and turgor, impaired hydraulic conductance, and higher stomatal resistance [139]. In their study on Cabernet Sauvignon, Choi et al. [140] reported that potted vines infected with Xf exhibited a significantly stronger transcriptional response of pathogen-induced genes when exposed to water deficit, as well as increased severity of disease symptoms and extent of pathogen colonisation. This agrees with the results of Thorne et al. [130] who found that vines inoculated with Xf and exposed to water deficit developed more extensive symptoms than when well-watered, as well as Choat et al. [141] who found a positive relationship between Xf concentration and symptom formation in deficit-irrigated vines. If, as some of these results indicate, stressed vines are more likely to express symptoms of vascular disease, then adopting a training method which avoids constriction of the vasculature of the cordon may help to limit the onset of disease

symptoms by avoiding a reduction in vine defence response. As of the present, however, the exact nature of the relationship between these factors of decline remains unclear.

4.3. Relationship between Strangulation and Trunk Disease

There is currently no published literature regarding the relationship if any that exists between constriction of the cordon from tight wrapping, dieback, and incidence of vascular disease. A small survey was conducted in the Waite Campus vineyard, University of Adelaide, South Australia in the spring of 2020 to investigate the relationship between cordon strangulation and fungal trunk disease expression. Fifteen-year-old Cabernet Sauvignon vines were assessed for the presence of characteristic Eutypa dieback foliar symptoms, comprising stunted shoots with chlorotic (yellow) leaves, often cupped and with tattered margins [142], as well as cordon dieback. From those assessed, two vines were selected which displayed cordon dieback but no foliar symptoms of Eutypa dieback, two vines were selected which displayed cordon dieback as well as foliar symptoms, and two vines were selected which were healthy in appearance and displayed no visible signs of dieback or foliar symptoms (Figure 3).



Figure 3. Presence of cordon dieback and foliar symptoms of Eutypa dieback. (**a**,**b**) Cordon dieback but no foliar symptoms; (**c**,**d**) cordon dieback and foliar symptoms (stunted shoots); (**e**,**f**) symptomless.

Based on visual examination, the cordons of all six vines appeared to have been established by tightly wrapping developing canes around the cordon wire, with the wire now visibly embedded within the wood of all cordons. Samples of approximately 15 cm length were cut from the cordons for cross section examination and for collection of samples for laboratory diagnosis by isolation. Upon direct examination of the cross sections, wedge patterns of staining were observed in the samples collected from the cordons displaying signs of dieback both in the presence and absence of characteristic Eutypa dieback foliar symptoms but were not observed in the samples collected from the cordons which were healthy in appearance (Figure 4).



Figure 4. Examination of cross sections. (**a**,**b**) Cordon dieback but no foliar symptoms; (**c**,**d**) cordon dieback and foliar symptoms; (**e**,**f**) symptomless.

This is logical when one considers that regardless of the cause of dieback (pathogen or strangulation) it is expected that dead wood will be observed in the cross section given that the wood is dying back. To diagnose if pathogens were present in the symptomatic wood, the cordon samples were surface disinfested in bleach before a drill was used to collect shavings made along the margin between live and dead wood. For the asymptomatic samples wood shavings were collected solely from wood which was healthy in appearance. Small sections of the shavings were then placed on potato dextrose agar plates and incubated for a week at 25 °C with a 12 h photoperiod before examination for the presence of fungal growth [136]. Eutypa lata was positively identified in plates from wood samples collected from cordons displaying dieback both in the presence and absence of foliar symptoms as well as from symptomless cordons. Additionally, other Diatrypaceous and Botryosphaeriaceous species were identified only in samples from cordons displaying Eutypa dieback foliar and dieback symptoms. These findings confirm the inherent difficulty in relying solely on the expression of foliar symptoms when investigating for the presence of fungal pathogens [127,135], as they may be present in symptomless vines, which are otherwise healthy in appearance. There remains a question as to what extent constriction of the cordon may influence the speed and severity at which symptoms of decline resulting from the presence of these pathogens are expressed, as such, more research is required.

5. Conclusions

A simple visual assessment of the cordon of a mature vine whose arms are wrapped so tightly that the cordon wire has long become embedded within the wood of the cordon is enough evidence for most observers to conclude that there has been a negative impact on the health of the vine. This situation is typically accompanied by various states of decay and dieback along with an oftentimes severe decline in productivity. In such a scenario, the constrictive effects of cordon strangulation may be working in conjunction with other factors such as the onset of vascular disease to drastically reduce yield and economic viability. It is for this reason that careful consideration must be given when planning and implementing cordon training techniques, both during the initial establishment of young vines as well as the reworking of older vineyards. Climate change is also an important consideration in this scenario, as heat and water stress may further exacerbate the factors driving cordon decline. Understanding the potential benefits of adopting cordon establishment techniques, which avoid constriction of the vine's vasculature, could provide vineyard managers with a strategy aimed at improving vineyard sustainability with little to no added consideration, input or cost after the initial period of establishment. Further research is required to investigate the impacts of wrapping developing arms tightly around the cordon wire in comparison to other cordon training techniques. This research would quantify the impacts of different cordon establishment techniques on vine health and longevity. Other considerations such as the benefits of adjusting the length of canes selected as permanent arms based on their apparent vigour before extending them to final length could also be investigated. By gaining a better understanding of the long-term advantages and disadvantages of different cordon establishment methods, growers in the future may be better equipped to avoid management decisions likely to lead to cordon decline and the costly, untimely reworking of vineyards.

Author Contributions: Conceptualization, P.O., C.C. and R.D.B.; methodology, P.O., C.C., R.D.B. and M.S.; formal analysis, P.O.; data curation, P.O.; writing—original draft preparation, P.O.; writing—review and editing, P.O., C.C., R.D.B. and M.S.; supervision, C.C. and R.D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the University of Adelaide and Wine Australia.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. All figures presented are original.

Acknowledgments: We would like to thank Wine Australia, who invest in and manage research, development and extension on behalf of Australia's grape growers and winemakers and the Australian Government. A special thank you to Ben Pike for his support in the assessment of vines in the Waite Campus vineyard.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Grigg, D.; Methven, D.; de Bei, R.; Rodríguez López, C.M.; Dry, P.; Collins, C. Effect of vine age on vine performance of Shiraz in the Barossa Valley, Australia. *Aust. J. Grape Wine Res.* 2017, 24, 75–87. [CrossRef]
- Vršič, S.; Ivančič, A.; Šušek, A.; Valdhuber, B.; Šiško, J.; Zagradišnik, M. The World's oldest living grapevine specimen and its genetic relationships. *Vitis* 2011, 50, 167–171.
- 3. Heymann, H.; Noble, A. Descriptive analysis of commercial Cabernet Sauvignon wines from California. *Am. J. Enol. Vitic.* **1987**, 38, 41–44.
- 4. Reynolds, A.G.; Pearson, E.G.; De Savigny, C.; Coventry, J.; Strommer, J. Interactions of vine age and reflective mulch upon berry, must, and wine composition of five *Vitis vinifera* cultivars. *Int. J. Fruit Sci.* **2008**, *7*, 85–119. [CrossRef]
- Bou Nader, K.; Stoll, M.; Rauhut, D.; Patz, C.D.; Jung, R.; Loehnertz, O.; Schultz, H.R.; Hilbert, G.; Renaud, C.; Roby, J.P.; et al. Impact of grapevine age on water status and productivity of *Vitis vinifera* L. cv. Riesling. *Eur. J. Agron.* 2019, *104*, 1–12. [CrossRef]
- 6. Rahman, L.; Creecy, H.; Orchard, B. Impact of citrus nematode (*Tylenchulus semipenetrans*) densities in soil on yield of grapevines (*Vitis vinifera* 'Shiraz') in south-eastern New South Wales. *Vitis* **2008**, *47*, 175–180.
- 7. Siebert, J. Eutypa: The economic toll on vineyards. Wines Vines 2001, 4, 50–56.
- 8. Sipiora, M.J.; Cuellar, S. Economic impact of Eutypa dieback. Wine Bus. Mon. 2014, 21, 46–49.
- 9. Sosnowski, M.R.; McCarthy, G. Economic impact of grapevine trunk disease management in Sauvignon blanc vineyards of New Zealand. *Wine Vitic. J.* 2017, *32*, 42.
- 10. Atallah, S.S.; Gomez, M.I.; Fuchs, M.F.; Martinson, T.E. Economic impact of grapevine leafroll disease on *Vitis vinifera* cv. Cabernet franc in Finger Lakes vineyards of New York. *Am. J. Enol. Vitic.* **2011**, *63*, 73–79. [CrossRef]
- 11. Credi, R.; Babini, A.R. Effects of virus and virus-like infections on growth, yield, and fruit quality of Albana and Trebbiano Romagnolo grapevines. *Am. J. Enol. Vitic.* **1997**, *48*, 7–12.
- 12. Ripamonti, M.; Pacifico, D.; Roggia, C.; Palmano, S.; Rossi, M.; Bodino, N.; Marzachì, C.; Bosco, D.; Galetto, L. Recovery from grapevine flavescence dorée in areas of high infection pressure. *Agronomy* **2020**, *10*, 1479. [CrossRef]
- 13. White, R.E. Understanding Vineyard Soils, 2nd ed.; Oxford University Press: New York, NY, USA, 2015.

- 14. Duchêne, E.; Schneider, C. Grapevine and climatic changes: A glance at the situation in Alsace. *Agron. Sustain. Dev.* **2005**, 25, 93–99. [CrossRef]
- 15. Jones, G.V.; White, M.A.; Cooper, O.R.; Storchmann, K. Climate change and global wine quality. *Clim. Chang.* **2005**, *73*, 319–343. [CrossRef]
- 16. Keller, M. Managing grapevines to optimise fruit development in a challenging environment: A climate change primer for viticulturists. *Aust. J. Grape Wine Res.* 2010, *16*, 56–69. [CrossRef]
- 17. Schultz, H.R. Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Aust. J. Grape Wine Res.* 2000, *6*, 2–12. [CrossRef]
- Caravia, L.; Collins, C.; Shepherd, J.; Tyerman, S. Wrapping arms for cordon establishment: Is it a stressful practice for grapevines? Wine Vitic. J. 2015, 30, 48–50.
- 19. Sperry, J.S. Evolution of water transport and xylem structure. Int. J. Plant. Sci. 2003, 164, S115–S127. [CrossRef]
- 20. Lucas, W.J.; Groover, A.; Lichtenberger, R.; Furuta, K.; Yadav, S.R.; Helariutta, Y.; He, X.Q.; Fukuda, H.; Kang, J.; Brady, S.M.; et al. The plant vascular system: Evolution, development and functions. *J. Integr. Plant Biol.* **2013**, *55*, 294–388. [CrossRef] [PubMed]
- 21. Dixon, H.H.; Joly, J. On the ascent of sap. *Philos. Trans. R. Soc. B* 1895, 186, 563–576.
- 22. Pickard, W.F. The ascent of sap in plants. Prog. Biophys. Mol. Biol. 1981, 37, 181–229. [CrossRef]
- 23. Brown, H.R. The theory of the rise of sap in trees: Some historical and conceptual remarks. *Phys. Perspect.* **2013**, *15*, 320–358. [CrossRef]
- Venturas, M.D.; Sperry, J.S.; Hacke, U.G. Plant xylem hydraulics: What we understand, current research, and future challenges. J. Integr. Plant. Biol. 2017, 59, 356–389. [CrossRef] [PubMed]
- 25. Tyree, M.T.; Sperry, J.S. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? *Plant. Physiol.* **1988**, *88*, 574–580. [CrossRef] [PubMed]
- Choné, X.; van Leeuwen, C.; Dubourdieu, D.; Gaudillère, J. Stem water potential is a sensitive indicator of grapevine water status. Ann. Bot. 2001, 87, 477–483. [CrossRef]
- 27. Tyree, M.T.; Ewers, F.W. The hydraulic architecture of trees and other woody plants. New Phytol. 1991, 119, 345–360. [CrossRef]
- 28. Evert, R.F. Esau's Plant. Anatomy: Meristems, Cells, and Tissues of the Plant. Body: Their Structure, Function, and Development, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2006.
- 29. Lovisolo, C.; Schubert, A. Effects of water stress on vessel size and xylem hydraulic conductivity in *Vitis vinifera* L. *J. Exp. Bot.* **1998**, *49*, 693–700.
- 30. Munitz, S.; Netzer, Y.; Shtein, I.; Schwartz, A. Water availability dynamics have long-term effects on mature stem structure in *Vitis vinifera*. *Am. J. Bot.* **2018**, *105*, 1443–1452. [CrossRef]
- 31. Ewers, F.W.; Fisher, J.B. Variation in vessel length and diameter in stems of six tropical and subtropical lianas. *Am. J. Bot.* **1989**, 76, 1452–1459. [CrossRef]
- 32. Jacobsen, A.L.; Pratt, R.B.; Tobin, M.F.; Hacke, U.G.; Ewers, F.W. A global analysis of xylem vessel length in woody plants. *Am. J. Bot.* 2012, *99*, 1583–1591. [CrossRef] [PubMed]
- Jacobsen, A.L.; Rodriguez-Zaccaro, F.D.; Lee, T.F.; Valdovinos, J.; Toschi, H.S.; Martinez, J.A.; Pratt, R.B. Grapevine xylem development, architecture, and function. In *Functional and Ecological Xylem Anatomy*; Hacke, U., Ed.; Springer International Publishing: Cham, Switzerland, 2015; pp. 133–162.
- 34. Sun, Q.; Rost, T.L.; Matthews, M.A. Pruning-induced tylose development in stems of current-year shoots of *Vitis vinifera* (Vitaceae). *Am. J. Bot.* **2006**, *93*, 1567–1576. [CrossRef]
- 35. Schultz, H.R.; Matthews, M.A. Xylem development and hydraulic conductance in sun and shade shoots of grapevine (*Vitis vinifera* L.): Evidence that low light uncouples water transport capacity from leaf area. *Planta* **1993**, *190*, 393–406. [CrossRef]
- 36. Tyree, M.T.; Sperry, J.S. Vulnerability of xylem to cavitation and embolism. Annu. Rev. Plant Biol. 1989, 40, 19–38. [CrossRef]
- Sun, Q.; Rost, T.L.; Matthews, M.A. Wound-induced vascular occlusions in *Vitis vinifera* (Vitaceae): Tyloses in summer and gels in winter. *Am. J. Bot.* 2008, 95, 1498–1505. [CrossRef] [PubMed]
- Bonsen, K.J.M.; Kučera, L.J. Vessel occlusions in plants: Morphological, functional and evolutionary aspects. *IAWA Bull.* 1990, 11, 393–399. [CrossRef]
- 39. Esau, K. Anatomy of Seed Plants, 2nd ed.; Wiley: New York, NY, USA, 1977.
- 40. Pérez-Donoso, A.G.; Lenhof, J.J.; Pinney, K.; Labavitch, J.M. Vessel embolism and tyloses in early stages of Pierce's disease. *Aust. J. Grape Wine Res.* **2016**, 22, 81–86. [CrossRef]
- 41. Dute, R.R.; Duncan, K.M.; Duke, B. Tyloses in abscission scars of loblolly pine. IAWA J. 1999, 20, 67–74. [CrossRef]
- 42. Saitoh, T.; Ohtani, J.; Fukazawa, K. The occurrence and morphology of tyloses and gums in the vessels of Japanese hardwoods. *IAWA J.* **1993**, *14*, 359–371. [CrossRef]
- 43. Schulz, A. Phloem. Structure related to function. In Progress in Botany; Springer: Berlin/Heidelberg, Germany, 1998; pp. 429-475.
- 44. Ruiz-Medrano, R.; Xoconostle-Cázares, B.; Lucas, W.J. The phloem as a conduit for inter-organ communication. *Curr. Opin. Plant. Biol.* **2001**, *4*, 202–209. [CrossRef]
- 45. Esau, K. Phloem structure in the grapevine, and its seasonal changes. Hilgardia 1948, 18, 217–296. [CrossRef]
- Gonzalez Antivilo, F.; Paz, R.C.; Tognetti, J.; Keller, M.; Cavagnaro, M.; Barrio, E.E.; Roig Juñent, F. Winter injury to grapevine secondary phloem and cambium impairs budbreak, cambium activity, and yield formation. *J. Plant. Growth Regul.* 2019, 39, 1095–1106. [CrossRef]

- 47. Esau, K. Anatomy and cytology of Vitis phloem. Hilgardia 1965, 37, 17–72. [CrossRef]
- 48. Bates, T.R.; Dunst, R.M.; Joy, P. Seasonal dry matter, starch, and nutrient distribution in 'Concord' grapevine roots. *HortScience* **2002**, *37*, 313–316. [CrossRef]
- 49. Zapata, C.; Deleens, E.; Chaillou, S.; Magne, C. Partitioning and mobilization of starch and N reserves in grapevine (*Vitis vinifera* L.). *J. Plant Physiol.* **2004**, *161*, 1031–1040. [CrossRef]
- 50. Holzapfel, B.P.; Smith, J.P. Developmental stage and climatic factors impact more on carbohydrate reserve dynamics of Shiraz than cultural practice. *Am. J. Enol. Vitic.* **2012**, *63*, 333–342. [CrossRef]
- 51. Aloni, R.; Raviv, A.; Peterson, C.A. The role of auxin in the removal of dormancy callose and resumption of phloem activity in *Vitis vinifera. Can. J. Bot.* **1991**, *69*, 1825–1832. [CrossRef]
- 52. Stoll, M. Effects of Partial Rootzone Drying on Grapevine Physiology and Fruit Quality. Ph.D. Thesis, University of Adelaide, Adelaide, Australia, 2000.
- Dry, P.R.; Loveys, B.R.; Botting, D.; Düring, H. Effects of partial root-zone drying on grapevine vigour, yield, composition of fruit and use of water. In Proceedings of the IX Australian Wine Industry Technical Conference, Adelaide, Australia, 16–19 July 1995; Winetitles: Adelaide, Australia, 1996; pp. 126–131.
- 54. Schultz, H.R.; Matthews, M.A. Resistance to water transport in shoots of *Vitis vinifera* L.: Relation to growth at low water potential. *Plant Physiol.* **1988**, *88*, 718–724. [CrossRef] [PubMed]
- 55. Tognetti, R.; Raschi, A.; Béres, C.; Fenyvesi, A.; Ridder, H.W. Comparison of sap flow, cavitation and water status of *Quercus petraea* and *Quercus cerris* trees with special reference to computer tomography. *Plant Cell Environ.* **1996**, *19*, 928–938. [CrossRef]
- 56. Dayer, S.; Prieto, J.A.; Galat, E.; Perez Peña, J. Carbohydrate reserve status of Malbec grapevines after several years of regulated deficit irrigation and crop load regulation. *Aust. J. Grape Wine Res.* **2013**, *19*, 422–430. [CrossRef]
- 57. Keller, M.; Romero, P.; Gohil, H.; Smithyman, R.P.; Riley, W.R.; Casassa, L.F.; Harbertson, J.F. Deficit irrigation alters grapevine growth, physiology, and fruit microclimate. *Am. J. Enol. Vitic.* **2016**, *67*, 426–435. [CrossRef]
- Rossouw, G.C.; Smith, J.P.; Barril, C.; Deloire, A.; Holzapfel, B.P. Implications of the presence of maturing fruit on carbohydrate and nitrogen distribution in grapevines under postveraison water constraints. J. Am. Soc. Hortic. Sci. 2017, 142, 71–84. [CrossRef]
- 59. Marciniak, M.; Reynolds, A.G.; Brown, R. Influence of water status on sensory profiles of Ontario Riesling wines. *Food Res. Int.* **2013**, *54*, 881–891. [CrossRef]
- 60. McCarthy, M.G. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **1997**, *3*, 2–8. [CrossRef]
- 61. Naor, A.; Bravdo, B.; Hepner, Y. Effect of post-veraison irrigation level on Sauvignon blanc yield, juice quality and water relations. *S. Afr. J. Enol. Vitic.* **1993**, *14*, 19–25. [CrossRef]
- 62. Romero, P.; Muñoz, R.G.; Fernández-Fernández, J.I.; del Amor, F.M.; Martínez-Cutillas, A.; García-García, J. Improvement of yield and grape and wine composition in field-grown Monastrell grapevines by partial root zone irrigation, in comparison with regulated deficit irrigation. *Agrar. Water Manag.* **2015**, *149*, 55–73. [CrossRef]
- Poni, S.; Lakso, A.N.; Turner, J.R.; Melious, R.E. Interactions of crop level and late season water stress on growth and physiology of field-growth Concord grapevines. *Am. J. Enol. Vitic.* 1994, 45, 252–258.
- 64. Lopez, G.; Girona, J.; Marsal, J. Response of winter root starch concentration to severe water stress and fruit load and its subsequent effects on early peach fruit development. *Tree Physiol.* **2007**, 27, 1619–1626. [CrossRef]
- 65. Smith, J.P.; Holzapfel, B.P. Cumulative responses of Semillon grapevines to late season perturbation of carbohydrate reserve status. *Am. J. Enol. Vitic.* **2009**, *60*, 461–470.
- 66. Dry, P.R. Canopy management for fruitfulness. Aust. J. Grape Wine Res. 2000, 6, 109–115. [CrossRef]
- 67. Bennett, J.; Jarvis, P.; Creasy, G.L.; Trought, M.C.T. Influence of defoliation on overwintering carbohydrate reserves, return bloom, and yield of mature Chardonnay grapevines. *Am. J. Enol. Vitic.* **2005**, *56*, 386–393.
- 68. Cox, C.M.; Favero, A.C.; Dry, P.R.; McCarthy, M.G.; Collins, C. Rootstock effects on primary bud necrosis, bud fertility, and carbohydrate storage in Shiraz. *Am. J. Enol. Vitic.* **2012**, *63*, 277–283. [CrossRef]
- 69. Nuzzo, V.; Matthews, M.A. Response of fruit growth and ripening to crop level in dry-farmed Cabernet Sauvignon on four rootstocks. *Am. J. Enol. Vitic.* **2006**, *57*, 314–324.
- Holzapfel, B.P.; Smith, J.P.; Field, S.K.; Hardie, W.J. Dynamics of carbohydrate reserves in cultivated grapevines. *Hortic. Rev.* 2010, 37, 143.
- 71. Guilpart, N.; Metay, A.; Gary, C. Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. *Eur. J. Agron.* **2014**, *54*, 9–20. [CrossRef]
- 72. Collins, C.; Rawnsley, B. Factors influencing primary bud necrosis (PBN) in Australian vineyards. In Proceedings of the VII International Symposium on Grapevine Physiology and Biotechnology, Davis, CA, USA, 21–25 June 2004; Volume 689, pp. 81–86.
- 73. Vasudevan, L.; Wolf, T.K.; Welbaum, G.G.; Wisniewski, M.E. Reductions in bud carbohydrates are associated with grapevine bud necrosis. *Vitis* **1998**, *37*, 189–190.
- 74. Collins, C.; Rawnsley, B. National survey reveals primary bud necrosis is widespread in Australian vineyards. *Aust. N. Z. Grapegrow. Winemak.* 2004, 485, 46–49.
- 75. Bernizzoni, F.; Gatti, M.; Civardi, S.; Poni, S. Long-term performance of Barbera grown under different training systems and within-row vine spacings. *Am. J. Enol. Vitic.* **2009**, *60*, 339–348.

- 76. Carbonneau, A.; Garrier, G.; Deloire, A. Quelques éléments historiques de l'évolution des architectures de vigne (première partie). Le Progrès Agric. Et Vitic. 2001, 118, 155–161.
- 77. Eltom, M.; Winefield, C.S.; Trought, M.C.T. Effect of pruning system, cane size and season on inflorescence primordia initiation and inflorescence architecture of *Vitis vinifera* L. Sauvignon blanc. *Aust. J. Grape Wine Res.* **2014**, *20*, 459–464. [CrossRef]
- Trought, M.C.T. Fruitset—Possible implications on wine quality. In Proceedings of the ASVO Transforming Flowers to Fruit Seminar, Mildura, Australia, 25 July 2005; pp. 32–36.
- 79. Jackson, D. Pruning and Training; Rev. ed.; Lincoln University Press: Lincoln, NZ, USA, 2001.
- 80. May, P.; Brien, C.J.; Clingeleffer, P.R. Pruning Sultana vines by the arched cane system. *Aust. J. Exp. Agric. Anim. Husb.* **1978**, 18, 301–308. [CrossRef]
- 81. Winkler, A.J.; Cook, J.A.; Kliewer, W.M.; Lider, L.A. General Viticulture; University of California Press: Berkeley, CA, USA, 1974.
- 82. Tassie, E.; Freeman, B.M. Pruning. In *Viticulture Volume 2, Practices*; Coombe, B.G., Dry, P.R., Eds.; Winetitles: Adelaide, Australia, 1992; pp. 66–84.
- Intrieri, C.; Poni, S. Integrated evolution of trellis training systems and machines to improve grape quality and vintage quality of mechanized Italian vineyards. Am. J. Enol. Vitic. 1995, 46, 116–127.
- Gasparinetti, P.; Biasi, W.; Teot, G.; Maschio, T.; Peratoner, C.; Bertamini, M. Materiali d'impianto in viticoltura: Un occhio ai particolari. *Inf. Agrar.* 1999, 55, 33–42.
- 85. Caravia, L. Heat Wave Mitigation Strategies for Wine Grape Production and Measures of the Impact of Heat on Berry Ripening and Wine Composition. Ph.D. Thesis, University of Adelaide, Adelaide, Australia, 2016.
- 86. Tombesi, S.; Farinelli, D. Trunk constriction effects on vegetative vigour and yield efficiency in olive tree (*Olea europaea* L.). *J. Agric. Sci. Technol.* **2016**, *18*, 1667–1680.
- Tombesi, S.; Farinelli, D.; Palliotti, A.; Poni, S.; DeJong, T.M. Xylem manipulation techniques affecting tree vigour in peach and olive trees. In Proceedings of the XI International Symposium on Integrating Canopy, Rootstock and Environmental Physiology in Orchard Systems, Bologna, Italy, 28 August–2 September 2016; Volume 1228, pp. 91–96.
- 88. Dann, I.R.; Wildes, R.A.; Chalmers, D.J. Effects of limb girdling on growth and development of competing fruit and vegetative tissues of peach trees. *Aust. J. Plant Physiol.* **1984**, *11*, 49–58. [CrossRef]
- Rufato, L.; Machado, B.D.; Luz, A.R.; Marcon Filho, J.L.; Hipólito, J.S.; Kretzschmar, A.A. Effect of trunk girdling on growth and crop yield of 'Packham's Triumph' pear. In Proceedings of the XII International Pear Symposium, Leuven, Belgium, 14–18 July 2014; Volume 1094, pp. 265–268.
- Sousa, R.; Calouro, F.; Oliveira, C. Influence of trunk girdling on growth and fruit production of 'Rocha' / BA29. In Proceedings of the X International Pear Symposium, Peniche, Portugal, 22–26 May 2007; Volume 800, pp. 319–324.
- 91. Day, K.R.; DeJong, T.M. Improving fruit size: Thinning and girdling nectarines, peaches, and plums. *Compact Fruit Tree* **1999**, 32, 49–51.
- 92. Jensen, F.; Swanson, F.; Peacock, W.; Leavitt, G. The effect of width of cane and trunk girdles on berry weight and soluble solids in table 'Thompson Seedless' vineyards. *Am. J. Enol. Vitic.* **1975**, *26*, 90–91.
- 93. Li, K.T.; Chang, J.C.; Wang, L.L.; Liu, Y.T.; Lee, C.L. Girdling improved berry coloration in summer but suppressed return growth in the following spring in "Kyoho" grapevines cultivated in the subtropical double cropping system. *Vitis* **2015**, *54*, 59–63.
- 94. Eltom, M.; Trought, M.C.T.; Winefield, C.S. The effects of cane girdling before budbreak on shoot growth, leaf area and carbohydrate content of *Vitis vinifera* L. Sauvignon blanc grapevines. *Funct. Plant Biol.* **2013**, *40*, 749–757. [CrossRef] [PubMed]
- 95. Castaldi, R. Prevenire l'invecchiamento del cordone della vite. Inf. Agrar. 2008, 4, 89–91.
- 96. Dry, P.R.; Loveys, B.R. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. *Aust. J. Grape Wine Res.* **1998**, *4*, 140–148. [CrossRef]
- 97. Castaldi, R. Vite: Mantenere funzionale il cordone permanente. Inf. Agrar. 2016, 2, 81–84.
- 98. Bernizzoni, F.; Civardi, S.; Van Zeller, M.; Gatti, M.; Poni, S. Shoot thinning effects on seasonal whole-canopy photosynthesis and vine performance in *Vitis vinifera* L. cv. Barbera. *Aust. J. Grape Wine Res.* **2011**, *17*, 351–357. [CrossRef]
- 99. Simonit, M.; Deledda, F.; Giudici, M.; Manfreda, L.; Ostan, M.; Turata, R.; Zanutta, A. Vite: Potatura «virtuosa» applicazione e vantaggi. *Inf. Agrar.* 2012, 37, 36–46.
- 100. Simonit, M.; Sirch, P. «Potatura soffi ce» contro il deperimento dei vigneti. Inf. Agrar. 2009, 36, 43-46.
- 101. Carter, M.V. *Eutypa armeniacae* Hansf. & Carter, sp. nov., an airborne vascular pathogen of *Prunus armeniaca* L. in southern Australia. *Aust. J. Bot.* **1957**, *5*, 21–35.
- 102. Lecomte, P.; Diarra, B.; Boisseau, M.; Weingartner, S.; Rey, P. Prévenir l'esca chez *Vitis vinifera* en proscrivant les modes de conduite ou les systèmes de taille mutilants. *IVES Tech. Rev. Vine Wine* 2021. [CrossRef]
- 103. Henderson, B.; Sosnowski, M.R.; McCarthy, M.G.; Scott, E.S. Incidence and severity of Eutypa dieback in grapevines are related to total surface area of pruning wounds. *Aust. J. Grape Wine Res.* **2020**, 27, 87–93. [CrossRef]
- 104. Faúndez-López, P.; Delorenzo-Arancibia, J.; Gutiérrez-Gamboa, G.; Moreno-Simunovic, Y. Pruning cuts affect wood necrosis but not the percentage of budburst or shoot development on spur pruned vines for different grapevine varieties. *Vitis* 2021, 60, 137–141.
- Cholet, C.; Bruez, É.; Lecomte, P.; Barsacq, A.; Martignon, T.; Giudici, M.; Simonit, M.; Dubourdieu, D.; Gény, L. Plant resilience and physiological modifications induced by curettage of Esca-diseased grapevines. *OENO One* 2021, 55, 153–169. [CrossRef]

- 106. Travadon, R.; Lecomte, P.; Diarra, B.; Lawrence, D.P.; Renault, D.; Ojeda, H.; Rey, P.; Baumgartner, K. Grapevine pruning systems and cultivars influence the diversity of wood-colonizing fungi. *Fungal Ecol.* **2016**, *24*, 82–93. [CrossRef]
- 107. Simonit, M.; Deledda, F.; Giudici, M.; Manfreda, L.; Ostan, M.; Turata, R.; Zanutta, A. Potatura vite: Il taglio è indipendente dalla forma di allevamento. *Inf. Agrar.* 2013, *36*, 32–35.
- 108. Simonit, M.; Deledda, F.; Giudici, M.; Manfreda, L.; Ostan, M.; Turata, R.; Zanutta, A. Pergola: Le conseguenze dei tagli di potatura. *Inf. Agrar.* 2013, *36*, 36–39.
- 109. Castaldi, R. Vite: Tendenza all'abbandono del cordone permanente. Inf. Agrar. 2011, 28, 58-60.
- 110. van Niekerk, J.M.; Bester, W.; Halleen, F.; Crous, P.W.; Fourie, P.H. The distribution and symptomatology of grapevine trunk disease pathogens are influenced by climate. *Phytopathol. Mediterr.* **2011**, *50*, 98–111.
- 111. Moller, W.J.; Kasimatis, A.N. Dieback of grapevines caused by Eutypa armeniacae. Plant. Dis. Rep. 1978, 62, 254–258.
- Trouillas, F.P.; Urbez-Torres, J.R.; Gubler, W.D. Diversity of diatrypaceous fungi associated with grapevine canker diseases in California. *Mycologia* 2010, 102, 319–336. [CrossRef] [PubMed]
- 113. Pitt, W.M.; Huang, R.; Steel, C.C.; Savocchia, S. Identification, distribution and current taxonomy of Botryosphaeriaceae species associated with grapevine decline in New South Wales and South Australia. *Aust. J. Grape Wine Res.* 2010, *16*, 258–271. [CrossRef]
- Úrbez-Torres, J.R.; Gubler, W.D. Pathogenicity of Botryosphaeriaceae species isolated from grapevine cankers in California. *Plant Dis.* 2009, *93*, 584–592. [CrossRef]
- 115. van Niekerk, J.M.; Crous, P.W.; Groenewald, J.Z.; Fourie, P.H.; Halleen, F. DNA phylogeny, morphology and pathogenicity of Botryosphaeria species on grapevines. *Mycologia* **2004**, *96*, 781–798. [CrossRef]
- 116. van Niekerk, J.M.; Groenewald, J.; Farr, D.; Fourie, P.; Halleer, F.; Crous, P. Reassessment of *Phomopsis* species on grapevines. *Australas. Plant Path.* **2005**, *34*, 27–39. [CrossRef]
- 117. Fischer, M. Biodiversity and geographic distribution of Basidiomycetes causing Esca-associated white rot in grapevine: A worldwide perspective. *Phytopathol. Mediterr.* **2006**, *45*, 30–42.
- Crous, P.W.; Gams, W.; Wingfield, M.J.; van Wyk, P.S. *Phaeoacremonium* gen. nov. associated with wilt and decline diseases of woody hosts and human infections. *Mycologia* 1996, *88*, 786–796. [CrossRef]
- 119. Travadon, R.; Lawrence, D.P.; Rooney-Latham, S.; Gubler, W.D.; Wilcox, W.F.; Rolshausen, P.E.; Baumgartner, K. *Cadophora* species associated with wood-decay of grapevine in North America. *Fungal Biol.* **2015**, *119*, 53–66. [CrossRef] [PubMed]
- 120. Gramaje, D.; Urbez-Torres, J.R.; Sosnowski, M.R. Managing grapevine trunk diseases with respect to etiology and epidemiology: Current strategies and future prospects. *Plant Dis.* **2018**, 102, 12–39. [CrossRef] [PubMed]
- 121. Larignon, P.; Dubos, B. Fungi associated with Esca disease in grapevine. Eur. J. Plant Pathol. 1997, 103, 147–157. [CrossRef]
- 122. Rolshausen, P.E.; Trouillas, F.; Gubler, W.D. Identification of Eutypa lata by PCR-RFLP. Plant. Dis. 2004, 88, 925–929. [CrossRef]
- 123. Urbez-Torres, J.R.; Leavitt, G.M.; Voegel, T.M.; Gubler, W.D. Identification and distribution of *Botryosphaeria* spp. associated with grapevine cankers in California. *Plant. Dis.* 2006, *90*, 1490–1503. [CrossRef]
- 124. Rolshausen, P.E.; Urbez-Torres, J.R.; Rooney-Latham, S.; Eskalen, A.; Smith, R.J.; Gubler, W.D. Evaluation of pruning wound susceptibility and protection against fungi associated with grapevine trunk diseases. *Am. J. Enol. Vitic.* **2010**, *61*, 113–119.
- 125. Chatelet, D.S.; Matthews, M.A.; Rost, T.L. Xylem structure and connectivity in grapevine (*Vitis vinifera*) shoots provides a passive mechanism for the spread of bacteria in grape plants. *Ann. Bot.* **2006**, *98*, 483–494. [CrossRef]
- 126. Sosnowski, M.R.; Ayres, M.; Wicks, T.; McCarthy, M. In search of resistance to grapevine trunk diseases. Wine Vitic. J. 2013, 28, 55.
- Sosnowski, M.R.; Shtienberg, D.; Creaser, M.L.; Wicks, T.J.; Lardner, R.; Scott, E.S. The influence of climate on foliar symptoms of Eutypa dieback in grapevines. *Phytopathology* 2007, 97, 1284–1289. [CrossRef]
- 128. Hopkins, D.L. Xylella fastidiosa: Xylem-limited bacterial pathogen of plants. Annu. Rev. Phytopathol. 1989, 27, 271–290. [CrossRef]
- 129. Sun, Q.; Sun, Y.; Walker, M.A.; Labavitch, J.M. Vascular occlusions in grapevines with Pierce's disease make disease symptom development worse. *Plant Physiol.* **2013**, *161*, 1529–1541. [CrossRef] [PubMed]
- 130. Thorne, E.T.; Stevenson, J.F.; Rost, T.L.; Labavitch, J.M.; Matthews, M.A. Pierce's disease symptoms: Comparison with symptoms of water deficit and the impact of water deficits. *Am. J. Enol. Vitic.* **2006**, *57*, 1–11.
- 131. Edwards, J.; Salib, S.; Thomson, F.; Pascoe, I.G. The impact of *Phaeomoniella chlamydospora* infection on the grapevine's physiological response to water stress—Part 1: Zinfandel. *Phytopathol. Mediterr.* **2007**, *46*, 26–37.
- 132. Edwards, J.; Salib, S.; Thomson, F.; Pascoe, I.G. The impact of *Phaeomoniella chlamydospora* infection on the grapevine's physiological response to water stress—Part 2: Cabernet Sauvignon and Chardonnay. *Phytopathol. Mediterr.* **2007**, *46*, 38–49.
- 133. Ferreira, J.H.S.; van Wyk, P.S.; Calitz, F.J. Slow dieback of grapevine in South Africa: Stress-related predisposition of young vines for infection by *Phaeoacremonium chlamydosporum*. S. Afr. J. Enol. Vitic. **1999**, 20, 43–46.
- 134. Fischer, M.; Kassemeyer, H.H. Water regime and its possible impact on expression of Esca symptoms in *Vitis vinifera*: Growth characters and symptoms in the greenhouse after artificial infection with *Phaeomoniella chlamydospora*. *Vitis* **2012**, *51*, 129–135.
- Sosnowski, M.R.; Luque, J.; Loschiavo, A.P.; Martos, S.; Garcia-Figueres, F.; Wicks, T.J.; Scott, E.S. Studies on the effect of water and temperature stress on grapevines inoculated with *Eutypa lata*. *Phytopathol. Mediterr.* 2011, 50, 127–138.
- 136. Sosnowski, M.R.; Ayres, M.; Scott, E. The influence of water deficit stress on the grapevine trunk disease pathogens *Eutypa lata* and *Diplodia seriata*. *Plant*. *Dis*. **2021**. [CrossRef]
- 137. Oswald, B. The Effect of Water Stress on Colonisation of Grapevines by *Eutypa lata*. Bachelor's Thesis, University of Adelaide, Adelaide, Australia, 2017.

- 138. Pouzoulet, J.; Scudiero, E.; Schiavon, M.; Rolshausen, P.E. Xylem vessel diameter affects the compartmentalization of the vascular pathogen *Phaeomoniella chlamydospora* in grapevine. *Front. Plant Sci.* **2017**, *8*, 1442. [CrossRef] [PubMed]
- 139. Goodwin, P.H.; Devay, J.E.; Meredith, C.P. Roles of water stress and phytotoxins in the development of Pierce's disease of the grapevine. *Physiol. Mol. Plant Pathol.* **1988**, *32*, 1–15. [CrossRef]
- 140. Choi, H.K.; Iandolino, A.; da Silva, F.G.; Cook, D.R. Water deficit modulates the response of *Vitis vinifera* to the Pierce's disease pathogen *Xylella fastidiosa*. *Mol. Plant-Microbe Interact*. **2013**, *26*, 643–657. [CrossRef] [PubMed]
- 141. Choat, B.; Gambetta, G.A.; Wada, H.; Shackel, K.A.; Matthews, M.A. The effects of Pierce's disease on leaf and petiole hydraulic conductance in *Vitis vinifera* cv. Chardonnay. *Physiol. Plant* **2009**, *136*, 384–394. [CrossRef]
- 142. Carter, M.V. *The Status of Eutypa Lata as a Pathogen;* Published on behalf of C.A.B. International; Mycological Institute by C.A.B. International: Wallingford, UK, 1991.