An Observational Study into the Recovery of Grapevines (*Vitis vinifera* L.) following a Bushfire

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Abstract: Bushfires occur worldwide, including regions in which winegrapes are grown. Recent research on grape and wine composition has demonstrated that wine made from smoke-affected grapes can be tainted. However, little is known about the impact of fire on grapevines, in particular the growth and recovery of grapevines scorched during a bushfire. In 2008, a vineyard in the southern Adelaide Hills region of South Australia was partially burned by a bushfire. Vegetative and reproductive measurements were taken for two cultivars, Pinot noir and Semillon (*Vitis vinifera* L.), in the subsequent growing seasons to compare the growth and development of scorched and unscorched vines. Reductions in shoot number, bunch number, bunch weight, pruning weight, and yield were observed for scorched vines compared with unscorched vines, in the season following the fire, but both cultivars showed improved signs of recovery two seasons after fire damage occurred. Fire-damaged vines produced lower crop yields due to decreased fruitfulness and berry numbers, and in the season after the bushfire, shoot development was mostly from buds located on the cordon, rather than buds of specific nodes retained after pruning. Elemental analysis of leaf tissue and juice was performed using inductively coupled plasma–optical emission spectrometry, but few meaningful compositional differences were observed. Smoke-derived volatile phenols and guaiacol glycoconjugates were also quantified by gas chromatography–mass spectrometry and high-performance–tandem mass spectrometry, respectively, to investigate the potential carryover of smoke taint between seasons. However, there was no evidence of sequestration of smoke components. Research findings will enable grapegrowers to facilitate the recovery of fire-damaged vines in subsequent seasons through modification of viticultural management practices, including pruning strategies such as retraining the cordon using cane-pruning techniques or leaving longer, more fruitful bearers to increase node number retained after pruning.

Key words: bushfire, grapevines, guaiacol, Semillon, Pinot noir, vine growth

Bushfires (or wildfires) occur throughout the world, typically playing an important role in the evolution and dynamics of ecosystems (Lloret et al. 2002). However, given that many vineyards are located in regions with prolonged hot and dry summers, conditions that are conducive to bushfires, it is perhaps not surprising that an increasing number of wine regions have reported vineyard exposure to bushfire smoke, both in Australia and overseas (Westerling et al. 2006, Whiting and Krstic 2007). Until recently, the effect of smoke exposure on grapevines had not been reported in the scientific literature. The link between grape exposure to smoke and an apparent taint in wine was first demonstrated in Verdelho grapes, following postharvest treatment with smoke (Kennison et al. 2007). Subsequent studies have largely focused on the analysis and/or amelioration of smoke taint in grapes and wine (Ristic et al. 2011, Wilkinson et al. 2011, Fudge et al. 2012), albeit the formation of necrotic lesions on leaves and decreased crop yield (in the subsequent growing season) have been reported in response to the application of smoke to grapevines under experimental conditions (Kennison et al. 2009, 2011). In some instances, however, vineyards have been subjected to fire damage rather than exposure to smoke.

Comparatively, very little is known about the impact of fire on grapevine physiology and, in particular, the growth and recovery of fire-damaged grapevines. Scarlett et al. (2011) investigated vineyard viability after a bushfire using visual assessments of leaf damage (the extent to which foliage was scorched by radiant heat) and the viability of cordon, trunk, and latent bud tissue. Anecdotal evidence from grapegrowers and vineyard managers suggests there is a reduction in the vegetative and reproductive growth of scorched vines in the seasons following a bushfire, but, to date, studies concerning the recovery of grapevines following a bushfire have not been reported in the literature.

In contrast, the impact of cold injury due to freeze events has been well studied, with damage ranging from bud injury to the loss of aboveground vine structure (Wolfe 2001), depending on the severity and duration of a freeze event. Cold injury can negatively affect crop yield and fruit composition in the season(s) following a freeze event (Keller and

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Mills 2007). However, grapevine recovery can be facilitated through viticultural management, with pruning, fertilization, irrigation, canopy management, and retraining practices found to influence the restoration of vine productivity (Wolfe 2001, Keller and Mills 2007). The extent of damage determines the most appropriate approaches to vineyard management, but where injury is either underestimated or overestimated, cultural practices may need to be adjusted accordingly.

Previous studies have shown that exposure to sulfur dioxide and ozone, common constituents of smoke (Heath 1980), can induce stomatal closure in grapevine leaves, the formation of necrotic lesions on leaf blades and in some cases total leaf necrosis, as well as reduced shoot growth (Rosen et al. 1978, Heath 1980, Shertz et al. 1980). Complete defoliation of grapevines can reduce fruit maturation rates, increase primary bud mortality, decrease fruitfulness, and delay spring budbreak (Mansfield and Howell 1981, Bennett et al. 2005), which are physiological responses associated with decreased concentrations of overwintering carbohydrate reserves in both the roots and trunk (Bennett et al. 2005). Variation in leaf and stem nutrient content during post-fire regeneration has also been observed in other plant species (Carreira and Niell 1992).

In March 2008, a vineyard in the southern Adelaide Hills region of South Australia was partially burned by a bushfire. This provided an opportunity to determine to what extent fire damage influences the growth and development of grapevines in subsequent growing seasons, investigate the factors which might contribute to any growth and/or yield differences, and assess longer-term vine recovery after a bushfire in order to devise appropriate management strategies that minimize the impact of a bushfire in the vineyard.

Materials and Methods

Vineyard site. An observational study was conducted in a vineyard located in Willunga (lat. 35°17´S; long. 138°35´E), in the Adelaide Hills wine region of South Australia, over two growing seasons: 2008–2009 and 2009–2010. The vineyard was partially burned in a bushfire that occurred on 13 Mar 2008, during the harvest period. A range of viticultural measurements and compositional analyses (described below) were performed on grapevines from two cultivars (*Vitis vinifera* L.), Semillon (SEM) and Pinot noir (PN), selected from burnt and unburnt areas of the vineyard. Conditional sampling of vines was used to minimize vine, site, and fire severity variability. For each cultivar, a block of scorched vines was deliberately chosen from the most severely burnt part of the vineyard. Each block comprised six adjacent vines by two adjacent rows, for a total of 12 vines. Individual vines served as treatment replicates. These vines were considered to be "scorched" according to the fire severity matrix reported by Keeley (2009) and exhibited complete leaf loss due to radiated heat (i.e., no green foliage remained) with light charring of the trunk and cordon. Additionally, the surrounding groundcover was charred or consumed and irrigation lines were damaged (melted). For each cultivar, a block of unscorched vines (12 replicates, as above) was similarly chosen from unburnt parts of the vineyard. Unscorched vines were deliberately chosen based on their close proximity to scorched vines (i.e., two buffer rows between rows of scorched and unscorched vines), but such that they did not exhibit any heat or fire damage (100% green foliage) or charring of the trunk or cordon, that surrounding groundcover was present, and that irrigation lines were undamaged and intact. Soil surveys conducted before vineyard establishment indicated that within each vineyard block, scorched and unscorched vines were situated within areas of soil uniformity. SEM (clone BV14) vines were planted in 1995 and PN (clone G8VZ) vines in 1997, both with 2.7 m row and 2.0 m vine spacings. Vines were grown on their own roots, trained to a bilateral cordon, vertical shoot-positioned (VSP) system, and hand-pruned to a two-node spur system. No shoot-thinning, cluster-thinning, or other canopy-management practices were applied during the study. Climate data, comprising monthly rainfall and monthly mean maximum temperature for Kuitpo Forest (lat. 35°10´S; long. 138°40´E), were obtained from the Australian Bureau of Meteorology (www.bom.gov.au) (Table 1).

Vegetative and reproductive measurements. Vegetative measurements included the number of shoots per vine (count, noncount, and shoots from the trunk base), internode length, cane diameter and weight, and pruning weight per vine (35–40 nodes per vine were retained to maintain pruning level used across the vineyard). Bunch number and yield were recorded at harvest for all vines. Harvested bunches (3 per vine: n = 36

Table 1 Mean maximum temperature and rainfall during the 2007–2008, 2008–2009, and 2009–2010 growing seasons.

Variable/season	Oct	Nov	Dec	Jan	Feb	Mar
Mean max temp (°C)						
Average[a]	18.3	21.9	23.5	26.1	25.8	23.1
2007–2008	19.3	23.3	25.5	26.5	23.2	27.7
2008–2009	20.3	20.3	21.7	28.3	27.4	23.4
2009–2010	17.5	26.7	24.6	27.0	27.0	24.3
Mean rainfall (mm)						
Average[a]	53.9	36.7	34.2	22.5	22.9	38.9
2007–2008	48.0	33.6	39.2	8.2	10.8	20.6
2008–2009	20.4	23.0	40.8	1.0	0.4	26.8
2009–2010	56.6	56.0	21.4	15.0	6.6	27.2

[a]Mean maximum temperatures between 1998 and 2013 and mean rainfall between 1998 and 2014.

per cultivar per season, except for scorched SEM in 2009, where n = 9, because the 12 scorched vine replicates produced only 9 bunches in total) were frozen (at -20°C) for bunch and berry measurements and juice analysis. Bunch weight, berry weight, average seed number, seeded berry number, seedless berry number, and live green ovaries (LGOs) (as defined in May 2004) were recorded for all frozen bunches within two months of harvest in each year of collection (May 2009 and 2010). The millerandage index (MI), a novel indicator of fruit set, was also calculated (Collins and Dry 2009). This index is an indicator of the proportion of all postflowering organs that develop into seedless berries or LGOs. The higher the numerical millerandage index, the greater the degree of expression of this reproductive condition.

Six representative shoots were collected from each vine at the time of dormant pruning (July 2009 and 2010), from which cane diameter and internode length were measured. Nodes one to four from the base of each shoot were then dissected under a light microscope and the number of inflorescence primordia (IP) in the primary bud (n+1) recorded to determine predicted fruitfulness. The incidence of primary bud necrosis (PBN) (expressed as a percentage) was also evaluated. The number of IP in the secondary bud (n+2) was counted and included in the measurement of total IP per node position only when the primary bud was necrotic. Actual fruitfulness was recorded as the number of bunches per node at harvest (March 2010 and 2011).

Elemental analysis. Elemental analysis was performed on 50 petioles and 10 mL juice samples obtained from six replicates (6 x 2 adjacent vines) from unscorched and scorched blocks of vines (as above) for each cultivar. Petioles were collected from leaves positioned at nodes four and five on shoots at fruit set in November 2008 and 2009, washed in reverse-osmosis water to remove any residues from fungicides, and subsequently dried for three days in an oven at 60°C, before grinding with an electrical grinder (LM1-P, Labtech Essa, Bassendean, Australia). Juice samples were prepared from a random sample of 150 berries, washed in reverse-osmosis water, and crushed in a juice press. The concentration of boron, calcium, copper, iron, magnesium, manganese, nitrogen, phosphorus, potassium, sodium, and zinc were quantified using an inductively coupled plasma–optical emission spectrometer (ICP–OES) (Optima 2100DV, PerkinElmer, Waltham, MA). ICP–OES analyses were performed by Waite Analytical Services (Adelaide, Australia) using methods reported previously (Wheal et al. 2011).

GC–MS analysis of volatile phenols. The smoke-derived volatile phenols guaiacol, 4-methylguaiacol, 4-ethylguaiacol, and 4-ethylphenol were quantified by gas chromatography–mass spectrometry (GC-MS) using stable isotope dilution assay (SIDA) methods reported previously (Pollnitz et al. 2000, 2004). Analyses were performed by the Australian Wine Research Institute Commercial Services Laboratory (Adelaide) using an Agilent 6890 gas chromatograph coupled to a 5973 mass selective detector (Agilent Technologies, Santa Clara, CA).

HPLC-MS/MS analysis of guaiacol glycoconjugates. Guaiacol glycoconjugates were quantified by high-performance liquid chromatography–tandem mass spectrometry (HPLC-MS/MS) using SIDA methods reported previously (Dungey et al. 2011). Analyses were performed using an Agilent 1200 HPLC system coupled to a 4000 Q TRAP hybrid tandem mass spectrometer.

Statistical analysis. Data were analyzed by analysis of variance (ANOVA) using Genstat (15th ed., VSN International Limited, Herts, UK). Mean comparisons were performed by least significant difference (LSD) multiple comparison test at $\alpha < 0.05$.

Results and Discussion

The mean maximum temperatures observed during the 2007–2008 growing season were comparable (±1.5°C) to the 15-year averages recorded for the region (Table 1), except for February, which was 2.6°C cooler, and March, which was 4.6°C warmer. However, the 10 days before the bushfire were unseasonably hot, with daily maximum temperatures between 32 and 37°C (data not shown). Average rainfall occurred early in the season (October to March) but conditions were much drier between January and March (Table 1), with no rainfall recorded in the three weeks before the fire (data not shown).

No changes were made to management practices applied to PN and SEM grapevines following the bushfire. Damaged irrigation lines were replaced (approximately two weeks after the fire) and winter pruning was carried out in July as is normal practice. A similar number of nodes were retained after pruning for unscorched and scorched vines of each cultivar, in each season (Table 2); however, considerable differences were subsequently observed between unscorched and scorched vines for the vine growth and yield component parameters that were measured. Some differences may reflect seasonal variation due to climate. Mean maximum temperatures in 2008–2009 and 2009–2010 were fairly typical (within ±2°C of average temperatures) except for February 2010, which was unusually warm (Table 1). The 2008–2009 season was dry, with only 112 mm rainfall recorded (compared to an average rainfall of 209 mm), whereas 183 mm was recorded in 2009–2010, but rainfall was considerably higher in September and October (113 mm) than between December and March (70 mm). The authors therefore acknowledge that the observational (rather than experimental) nature of the study allows inference to association and not causation, such that there may have been other confounding factors that were not apparent. Nevertheless, that such large differences in viticultural measurements were observed was considered to be of both interest and importance.

Effect of fire damage on vine growth. Total shoot number per vine was lower for scorched PN vines in both seasons, but a 30% increase in shoot number was observed in the second season (Table 2). Shoot number was also lower for scorched SEM vines in the first season, but vines had almost fully recovered in the second season. For both cultivars, the increased shoot number of scorched vines in the second season was largely due to an increase in the number of shoots arising from nodes retained after pruning (i.e., count shoots): almost no count shoots were observed for scorched vines in the first season, as the % bud kill from the fire was 97.5% for PN and 98.7% for SEM. There was very little difference in the number of noncount shoots (shoots arising from the cordon of the vines, rather than from spurs retained after pruning), irrespective of treatment or season. The number of shoots arising from the base of the trunk was higher for scorched PN vines than for unscorched PN vines, but decreased from the first to the second season. An increase in shoots arising from the base of the trunk of scorched SEM vines was observed in the second season, but it was not a statistically significant increase ($p = 0.079$). A high proportion of shoots arising from either the cordon or trunk of the vine, rather than from nodes retained at pruning, is considered to be an indication that pruning was too severe, buds retained at pruning were not viable or fertile, and/or that the grapevine was directing more reserves to vegetative growth rather than reproductive (Smart and Robinson 1991, Chaves et al. 2007).

Cane weight can also be used to evaluate vine growth and balance. For moderate shoot vigor, cane weight typically ranges between 20 and 40 g, whereas cane weights higher than 60 g indicate high shoot vigor and suggest vine imbalance (Smart and Robinson 1991). In the current study, shoot numbers were different between scorched and unscorched SEM vines, but pruning weights were similar in both seasons, due to the high cane weights, greater cane diameter and longer internodes of scorched vines, compared with unscorched vines (Table 2). Pinot noir pruning weights of scorched vines were lower than unscorched vines in the season following the fire due to lower shoot numbers per vine; PN cane weights were similar in the first season. In the second season cane weights of unscorched vines had lower cane weights, but larger cane diameter and longer internodes. Longer cane internode lengths were observed for scorched vines in the first season (irrespective of cultivar), which also indicated shoot vigor differences between scorched and unscorched vines. These results demonstrate the negative impact of scorching on vine structure in the seasons following fire damage, but also the recovery of vines with time.

For both cultivars, yield was also dramatically affected in the season following scorching, with only 0.2 and 0.1 kg/vine produced by PN and SEM vines, respectively (Table 2). Yields improved in the second season: scorched PN and SEM vines produced 8.4 and 3.8 kg/vine, respectively, at 55% and 35% of their corresponding unscorched vines, respectively. The fresh weight to pruning weight ratio (FW/PW) is another viticultural measurement commonly used to determine vine balance (Winkler et al. 1974, Bravdo et al. 1984, Smart and Robinson 1991). Scorched PN and SEM vines had extremely low FW/PW ratios in the first season, demonstrating a shift toward vegetative rather than reproductive growth and/or that fruitful buds were damaged and the remaining buds were predominantly infertile. In the second season, the FW/PW ratio of scorched vines was still lower than that of unscorched vines, but within the range at which vines are considered to be in balance (Bravdo et al. 1984, Smart and Robinson 1991). Interestingly, unscorched SEM vines had a very high FW/PW ratio, indicating that these vines may actually have been overcropped (Bravdo et al. 1984).

Table 2 Growth measures of unscorched and scorched Semillon and Pinot noir vines in two seasons following fire damage.

		Semillon[a]			Pinot noir[a]		
Variable	**Season**	**Unscorched**	**Scorched**	***p* value**	**Unscorched**	**Scorched**	***p* value**
2-node spurs retained at pruning	2009	17 ± 2.8	16 ± 2.3	ns	19 ± 4.3 a	15 ± 3.5 b	0.042
	2010	17 ± 2.2	18 ± 4.5	ns	20 ± 5.1	18 ± 3.1	ns
Shoot number at base of vine trunk	2009	0.6 ± 1.2	0.4 ± 0.5	ns	3.3 ± 2.4 b	5.8 ± 2.0 a	0.016
	2010	0.2 ± 0.2	2.4 ± 1.1	ns	1.9 ± 1.5	3.2 ± 3.2	ns
Shoot number/vine	2009	59 ± 8.3 a	16 ± 4.1 b	<0.001	72 ± 13.0 a	24 ± 9.9 b	<0.001
	2010	67 ± 9.8	60 ± 6.9	ns	84 ± 12.1 a	53 ± 13.3 b	<0.001
Count shoot number/vine	2009	36 ± 10.0 a	0.4 ± 1.4 b	<0.001	41 ± 9.8 a	1 ± 2.8 b	<0.001
	2010	50 ± 6.8 a	36 ± 5.7 b	0.022	57 ± 12.1 a	34 ± 10.5 b	<0.001
Noncount shoot number/vine	2009	24 ± 8.0 a	16 ± 4.9 b	0.011	31 ± 8.8 a	23 ± 7.9 b	0.036
	2010	15 ± 4.1	24 ± 6.1	ns	28 ± 9.9 a	19 ± 9.0 b	0.043
Pruning wt (kg/vine)	2009	1.3 ± 0.2	1.3 ± 0.3	ns	1.5 ± 0.3 a	0.6 ± 0.2 b	<0.001
	2010	0.7 ± 0.1 b	0.9 ± 0.2 a	0.007	1.2 ± 0.2	1.1 ± 0.2	ns
Cane wt (g)	2009	23 ± 5.9 b	80 ± 28 a	<0.001	21 ± 3.4	25 ± 8.0	ns
	2010	11 ± 2.1 b	14 ± 2.4 a	0.011	14 ± 2.5 b	22 ± 6.5 a	0.019
Cane diameter (mm)	2009	8.4 ± 0.1 b	9.4 ± 0.1 a	<0.001	8.6 ± 0.6 a	7.0 ± 0.5 b	<0.001
	2010	9.6 ± 0.3	9.6 ± 0.1	ns	8.9 ± 0.4 a	8.1 ± 0.3 b	<0.001
Internode length (mm)	2009	59 ± 2.3 b	80 ± 2.4 a	<0.001	59 ± 6.5 b	93 ± 7.8 a	<0.001
	2010	49 ± 3.1	49 ± 3.4	ns	73 ± 4.5 a	65 ± 3.7 b	0.004
Yield (kg/vine)	2009	5.0 ± 1.7 a	0.1 ± 0.1 b	<0.001	7.9 ± 2.7 a	0.2 ± 0.2 b	<0.001
	2010	11.7 ± 2.1 a	3.8 ± 2.2 b	<0.001	14.5 ± 5.6 a	8.4 ± 3.4 b	0.006
Fruit wt/pruning wt	2009	3.9 ± 1.4 a	0.04 ± 0.04 b	<0.001	5.4 ± 2.4 a	0.3 ± 0.2 b	<0.001
	2010	17.2 ± 2.2 a	5.2 ± 1.3 b	<0.001	12.5 ± 4.1 a	8.4 ± 3.2 b	0.029

[a]Data are means (n = 12) ± standard deviation (except for cane diameter and internode length, where n = 72). Values followed by different letters are significantly different (compared by cultivar and season); ns = not significant.

Effect of fire damage on yield components. The lower yields observed for scorched PN and SEM vines in the seasons following the bushfire were due to both lower bunch numbers per vine and lower bunch weights (Table 3). In the season following the bushfire, scorched PN vines yielded seven bunches, while scorched SEM vines yielded only one bunch, which equated to 91% and 98% reductions in bunch numbers compared to unscorched PN and SEM vines, respectively. Scorched vines showed signs of improved reproductive growth in the second season, with only 32% and 57% reductions in bunch numbers for PN and SEM, respectively. The average bunch weight of scorched vines was lower than for unscorched vines in the two seasons that followed the bushfire. However, in the second season, differences in bunch weight were much less apparent due to the improved berry numbers and berry weights observed for both cultivars (Table 3). Interestingly, the berry weight of scorched SEM vines was higher than for unscorched SEM vines in the first season, possibly in response to the increased shoot vigor and reduced bunch numbers or perhaps as compensation to reduced fruit set. These results were further supported by consideration of rachis weight, which can also be used as an indicator of bunch size (Dunn and Martin 2007). Differences in the rachis weight of unscorched and scorched vines were observed in the first season after the bushfire but not in the second season. The reproductive recovery of PN and SEM grapevines can be largely attributed to the increased shoot numbers (Table 2) and fruitfulness (bunch number per shoot; Table 4) observed in the 2010 season. These

Table 3 Reproductive measures of unscorched and scorched Semillon and Pinot noir vines in two seasons following fire damage.

		Semillon[a]			Pinot noir[a]		
Variable	Season	Unscorched	Scorched	*p* value	Unscorched	Scorched	*p* value
Yield (kg/vine)	2009	5.0 ± 1.7 a	0.1 ± 0.1 b	<0.001	7.9 ± 2.7 a	0.2 ± 0.2 b	<0.001
	2010	11.7 ± 2.1 a	3.8 ± 2.2 b	<0.001	14.5 ± 5.6 a	8.4 ± 3.4 b	0.006
Bunch number/vine	2009	57 ± 14.1 a	1 ± 1.2 b	<0.001	79 ± 16.4 a	7 ± 6.9 b	<0.001
	2010	75 ± 23.3 a	32 ± 20.7 b	<0.001	104 ± 22.6 a	70 ± 17.5 b	<0.001
Bunch wt (g)	2009	93 ± 37.4 a	37 ± 33.6 b[b]	0.012	98 ± 24.1 a	30 ± 12.9 b	<0.001
	2010	152 ± 37.6 a	117 ± 38.4 b	0.028	137 ± 45.8	120 ± 44.4	ns
Rachis wt (g)	2009	4.2 ± 2.2 a	1.5 ± 1.2 b[b]	0.022	4.1 ± 0.8 a	2.4 ± 0.9 b	<0.001
	2010	2.7 ± 0.7	2.4 ± 0.8	ns	4.0 ± 1.1	4.1 ± 1.4	ns
Total berry number	2009	97 ± 26.0 a	30 ± 22.1 b[b]	<0.001	113 ± 33.1 a	53 ± 18.6 b	<0.001
	2010	112 ± 19.1	95 ± 40.8	ns	129 ± 38.3	115 ± 29.1	ns
Seeded berries	2009	50 ± 21.3 a	24 ± 21.4 b[b]	0.040	94 ± 21.6 a	39 ± 14.4 b	<0.001
	2010	73 ± 14.4	64 ± 24.7	ns	129 ± 38.1	113 ± 30.3	ns
Seedless berries	2009	48 ± 9.4 a	6 ± 4.1 b[b]	<0.001	19 ± 15.3	14 ± 8.1	ns
	2010	39 ± 14.2	31 ± 20.2	ns	0.4 ± 0.4	2 ± 2.8	ns
Live green ovaries	2009	3.0 ± 5.1	0.8 ± 1.3[b]	ns	0.1 ± 0.1	0.3 ± 0.8	ns
	2010	13.7 ± 6.4 a	4.5 ± 3.8 b	<0.001	1.4 ± 1.2	1.6 ± 1.8	ns
Seed number/berry	2009	1.4 ± 0.4	1.2 ± 0.2[b]	ns	1.8 ± 0.3 a	1.1 ± 0.2 b	<0.001
	2010	1.4 ± 0.1	1.5 ± 0.1	ns	1.8 ± 0.2	1.7 ± 0.2	ns
Millerandage index	2009	5.2 ± 1.0 a	2.4 ± 2.3 b[b]	0.003	1.6 ± 0.8 b	2.7 ± 1.3 a	0.029
	2010	4.1 ± 0.8 a	3.2 ± 1.2 b	0.024	0.2 ± 0.1	0.3 ± 0.4	ns
Berry wt (g)	2009	0.89 ± 0.1 b	1.14 ± 0.2 a[b]	0.027	0.85 ± 0.17 a	0.52 ± 0.13 b	<0.001
	2010	1.35 ± 0.1	1.32 ± 0.2	ns	1.03 ± 0.19	0.99 ± 0.19	ns

[a]Data are means ± standard deviation (n = 12 for yield and bunch number per vine data; n = 36 for bunch and berry parameters (i.e., measurements from 3 bunches/vine replicate), except for 2009 scorched SEM data, where [b]n = 9 (measurements from 9 bunches/12 vine replicates). Values followed by different letters are significantly different (compared by cultivar and season); ns = not significant.

Table 4 Bud fertility measures of unscorched and scorched Semillon and Pinot noir vines in the seasons following fire damage.

		Semillon[b]			Pinot noir[b]		
Variable[a]	Season	Unscorched	Scorched	*p* value	Unscorched	Scorched	*p* value
Predicted fruitfulness	2010	1.21 ± 0.3	0.52 ± 0.3	ns	1.27 ± 0.4 b	1.43 ± 0.5 a	0.038
	2011	1.62 ± 0.4 a	1.23 ± 1.0 b	<0.001	1.33 ± 0.5	1.48 ± 0.5	ns
Actual fruitfulness	2010	1.13 ± 0.1 a	0.54 ± 0.2 b	<0.001	1.23 ± 0.2	1.34 ± 0.2	ns
	2011	1.51 ± 0.1 a	1.22 ± 0.1 b	<0.001	1.35 ± 0.2	1.41 ± 0.1	ns
% Primary bud necrosis	2010	9.0 ± 12.8 a	3.4 ± 8.7 b	0.003	21.5 ± 22.3	25.7 ± 21.8	ns
	2011	4.2 ± 10.3 b	25.4 ± 24.6 a	<0.001	15.6 ± 20.7	20.5 ± 20.7	ns

[a]Predicted fruitfulness is the mean number of inflorescence primordia at node positions 1–4 on dormant canes at pruning. Actual fruitfulness is the mean number of bunches per shoot at harvest. % Primary bud necrosis is the percentage of necrotic buds at node positions 1–4 on dormant canes at pruning.

[b]Data are means (n = 72) ± standard deviation. Values followed by different letters are significantly different (compared by cultivar and season); ns = not significant.

results suggest that vine fruitfulness and fruit set were negatively impacted by scorching but that vines had recovered considerably by the second growing season.

The condition known as "millerandage" occurs when the growth of grape berries is interrupted early in their development and suggests that reproductive processes have been disrupted (May 2004). By harvest, berries in the same bunch will be different sizes, with some particularly small and often seedless. Anatomical studies have revealed that interrupted growth can occur at different stages of berry development and that hormonal factors might be involved (Colin et al. 2002). In the current study, the millerandage index was determined for unscorched and scorched PN and SEM vines. Scorched PN vines had a higher proportion of seedless and LGOs compared to seeded berry number, which resulted in higher millerandage than unscorched vines (Table 3), but only in the first season. In contrast, the opposite was observed for SEM vines, with bunches from unscorched SEM vines containing a high proportion of seedless berries, such that the millerandage index was greater than for scorched SEM vines. These results suggest a varietal response in terms of reproductive performance, in agreement with previous studies (Dry et al. 2010). However, the extent to which scorching affected reproduction was difficult to quantify, given the significant reductions in total berry number resulting from the fire damage.

Bud dissections were performed in 2009 and 2010 to assess bud fertility and fruitfulness for the 2009–2010 and 2010–2011 seasons, respectively (Table 4). Bud dissections performed on PN canes suggested differences in the fruitfulness of unscorched and scorched vines, with scorched vines found to be slightly more fruitful than unscorched vines. Irrespective of cultivar, the actual fruitfulness of scorched vines was almost the same as unscorched vines in the 2010–2011 season. These results further demonstrate the recovery of scorched vines, evidenced by vegetative (Table 2) and reproductive (Table 3) measurements. Interestingly, scorched SEM vines had higher PBN in the second season compared to unscorched vines. Previous studies have shown a positive relationship between PBN and shoot vigor (Dry and Coombe 1994). However, our findings did not support this relationship, since shoot vigor, including cane weight, internode length, and pruning weight, were not meaningfully different between scorched and unscorched vines in the second season. However, the FW/PW ratio of scorched SEM vines was much lower than for unscorched vines, indicating scorched vines had more vegetative growth than reproductive growth in the second season. No differences in the incidence of PBN were observed between scorched and unscorched PN vines.

Elemental analysis of petioles and juice. Elemental analysis of petiole and juice samples from unscorched and scorched PN and SEM vines was performed, as variation in the leaf and stem nutrient content has been previously observed during post-fire regeneration of several shrub species (Carreira and Niell 1992) and given the importance of certain elements to the structural framework of vines, the capture and use of light energy, and various other chemical reactions

Table 5 Leaf tissue elemental analysis for unscorched and scorched Semillon and Pinot noir vines in two seasons following fire damage.

		Semillon[a]			Pinot noir[a]			Adequate nutrient concn[b]
Variable	Season	Unscorched	Scorched	*p* value	Unscorched	Scorched	*p* value	
N (%)	2009	2.5 ± 0.1	2.4 ± 0.1	ns	2.4 ± 0.1	2.5 ± 0.1	ns	2.2–4.0
	2010	2.4 ± 0.2	2.5 ± 0.2	ns	2.4 ± 0.2	2.2 ± 0.5	ns	
P (%)	2009	0.15 ± 0.008	0.16 ± 0.005	ns	0.14 ± 0.002	0.14 ± 0.004	ns	0.15–0.3
	2010	0.15 ± 0.009	0.15 ± 0.01	ns	0.21 ± 0.01 a	0.16 ± 0.01 b	0.006	
K (%)	2009	0.8 ± 0.08 b	1.1 ± 0.04 a	0.012	0.8 ± 0.14	0.9 ± 0.16	ns	0.8–1.6
	2010	0.8 ± 0.08	0.8 ± 0.1	ns	0.7 ± 0.03 b	0.9 ± 0.12 a	0.023	
Ca (%)	2009	2.4 ± 0.1 a	1.6 ± 0.07 b	<0.001	2.2 ± 0.15 a	1.8 ± 0.09 b	0.015	1.8–3.2
	2010	2.5 ± 0.2	2.3 ± 0.2	ns	2.5 ± 0.15	2.2 ± 0.15	ns	
Mg (%)	2009	0.6 ± 0.08	0.6 ± 0.02	ns	0.7 ± 0.04 a	0.5 ± 0.03 b	0.021	0.3–0.6
	2010	0.7 ± 0.03 b	0.8 ± 0.01 a	0.006	0.7 ± 0.01 a	0.5 ± 0.05 b	0.021	
Na (%)	2009	0.11 ± 0.01	0.09 ± 0.007	ns	0.05 ± 0.004	0.09 ± 0.002	ns	<0.1
	2010	0.06 ± 0.002	0.05 ± 0.006	0.032	0.04 ± 0.002	0.06 ± 0.013	ns	
Mn (mg/kg)	2009	42 ± 4 a	27 ± 5 b	0.019	84 ± 12	56 ± 18	ns	25–200
	2010	59 ± 1	58 ± 6	ns	149 ± 41	81 ± 33	ns	
B (mg/kg)	2009	41 ± 2	45 ± 2	ns	27 ± 2	23 ± 3	ns	35–100
	2010	47 ± 3	40 ± 6	ns	51 ± 11 a	22 ± 1 b	0.01	
Cu (mg/kg)	2009	41 ± 0 a	30 ± 0 b	0.022	40 ± 4	41 ± 5	ns	10–300
	2010	42 ± 1	39 ± 5	ns	62 ± 9	70 ± 27	ns	
Zn (mg/kg)	2009	13 ± 2	13 ± 1	ns	20 ± 8	14 ± 0.5	ns	30–60
	2010	17 ± 1	17 ± 1	ns	16 ± 4	21 ± 2	ns	
Fe (mg/kg)	2009	93 ± 10	81 ± 10	ns	125 ± 26	134 ± 7	ns	na
	2010	160 ± 9	180 ± 45	ns	260 ± 56	227 ± 28	ns	

[a]Data are means (n = 6) ± standard deviation. Values followed by different letters are significantly different (compared by cultivar and season); ns = not significant.
[b]As reported for grapevine leaf tissue (Robinson 1992); na = data not available.

that occur within plant cells (Robinson 1992). Several statistically significant differences in elemental composition were observed for PN and SEM petiole (Table 5) and juice (Table 6) samples. Large differences (≥50%) were observed for the sodium (in season 1 and 2) and boron (in season 2) content of PN petioles (Table 5) and for the iron and copper (in season 1) and sodium and manganese (in season 2) content of PN juice (Table 6). The copper (in season 1) and phosphorus and manganese (in season 2) content of SEM juice differed considerably (≥50%). Other smaller differences were observed in the vine and berry nutrient status of PN and SEM juice and petiole samples, but there were no apparent trends that could be readily attributed to the scorching of vines. Furthermore, with the exception of zinc, which was low in both scorched and unscorched vines, the nutrient content of all petiole samples was within the adequate nutrient concentration levels reported by Robinson (1992). Variation in the elemental composition of petioles and juice derived from the same cultivar is not unusual. Indeed, recent research highlighted stark contrasts in the vine nutrient status and berry nutrient content of Cabernet Sauvignon (Bramley et al. 2011).

Potential carryover of smoke taint between growing seasons. Anecdotal evidence from grapegrowers and winemakers has suggested that smoke taint might be carried over from one growing season to the next; that is, that smoke-derived volatile compounds might be sequestered by grapevines in the season in which smoke exposure occurs and remobilized in the subsequent season. To investigate this hypothesis, the fruit produced by scorched vines in the season following the fire (2008–2009) was analyzed by GC–MS and HPLC–MS/MS to screen for smoke-derived volatile phenols and glycoconjugate precursors of guaiacol, respectively. Trace levels of guaiacol (1 and 2 μg/L) were detected in two PN grape samples only; volatile phenols were not detected in any other samples. Quantification of guaiacol glycoconjugates is considered a more effective method of assessing smoke exposure of grapes (Wilkinson et al. 2011), given the glycoconjugation of smoke-derived volatile phenols following grapevine exposure to smoke (Dungey et al. 2011). In the current study, guaiacol glycoconjugates were not detected in fruit harvested from scorched PN or SEM grapevines and, as such, there was no evidence to suggest the sequestration of smoke components between growing seasons.

Conclusion

When grapevines are scorched, there are repercussions for both vegetative and reproductive growth in the subsequent growing seasons, but vines have the capacity to recover with time. A similar response has been observed in grapevines with cold injury following freezing events. As is the case with cold-injury damage, it may be possible to improve recovery times by adapting viticultural management practices, such as pruning strategies. For example, for spur-pruned vineyards, retraining the cordon using cane-pruning techniques may facilitate a more rapid return to previous crop levels. It may also be beneficial to leave longer, more fruitful bearers at pruning and/or to increase the number of nodes retained after pruning to improve vine recovery.

Table 6 Juice elemental analysis for unscorched and scorched Semillon and Pinot Noir vines in two seasons following fire damage.

		Semillon[a]			Pinot noir[a]		
Variable	Season	Unscorched	Scorched	*p* value	Unscorched	Scorched	*p* value
N (mg/L)	2009	152 ± 8	138 ± 12	ns	161 ± 8	172 ± 6	ns
	2010	143 ± 16	142 ± 11	ns	132 ± 21	145 ± 11	ns
P (mg/L)	2009	107 ± 9	142 ± 44	ns	168 ± 14	196 ± 21	ns
	2010	107 ± 16 b	161 ± 15 a	0.014	131 ± 15 b	159 ± 4 a	0.037
K (mg/L)	2009	556 ± 6	717 ± 237	ns	917 ± 25 b	1320 ± 157 a	0.012
	2010	1107 ± 57	1226 ± 124	ns	980 ± 120	1123 ± 35	ns
Ca (mg/L)	2009	118 ± 21	83 ± 11	ns	87 ± 12	81 ± 3	ns
	2010	85 ± 6 a	60 ± 5 b	0.006	64 ± 2 a	43 ± 5 b	0.003
Mg (mg/L)	2009	110 ± 5	121 ± 11	ns	142 ± 16	123 ± 9	ns
	2010	99 ± 8	91 ± 8	ns	100 ± 3	72 ± 8	0.005
Na (mg/L)	2009	70 ± 14	53 ± 6	ns	30 ± 5	37 ± 13	ns
	2010	38 ± 8	30 ± 3	ns	26 ± 3 b	48 ± 2 a	<0.001
Mn (mg/L)	2009	0.3 ± 0.1	0.3 ± 0.1	ns	0.5 ± 0.04	0.3 ± 0.1	ns
	2010	0.4 ± 0.03 a	0.2 ± 0.02 b	0.002	0.6 ± 0.02 a	0.3 ± 0.04 b	<0.001
B (mg/L)	2009	5.0 ± 0.6	6.5 ± 1.4	ns	4.0 ± 0.5 b	5.2 ± 0.3 a	0.017
	2010	4.9 ± 0.5	6.1 ± 1.1	ns	3.4 ± 0.1	3.6 ± 0.4	ns
Cu (mg/L)	2009	0.2 ± 0.02 b	0.5 ± 0.1 a	0.006	0.2 ± 0.04 b	0.3 ± 0.03 a	0.04
	2010	0.5 ± 0.05	0.5 ± 0.05	ns	0.5 ± 0.04	0.5 ± 0.1	ns
Zn (mg/L)	2009	0.4 ± 0.03	0.4 ± 0.1	ns	0.4 ± 0.1	0.4 ± 0.1	ns
	2010	0.4 ± 0.01	0.4 ± 0.04	ns	0.3 ± 0.01	0.2 ± 0.03	ns
Fe (mg/L)	2009	1.0 ± 0.1	0.7 ± 0.3	ns	1.1 ± 0.4	1.9 ± 1.1	ns
	2010	1.0 ± 0.3	0.6 ± 0.1	ns	0.8 ± 0.2	0.7 ± 0.1	ns

[a]Data are means (n = 6) ± standard deviation. Values followed by different letters are significantly different (compared by cultivar and season); ns = not significant.

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