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ORIGINAL RESEARCH ARTICLE

Grapevine recovery after fire and a first look at rapid damage assessment with satellite imagery

Cassandra Collins[1,2], Michaela Ritchie[3], Annette James[1], Patrick O'Brien[1], Saisai Ma[3], Roberta De Bei[1] and Andy Clarke[3]

[1] School of Agriculture, Food and Wine, Waite Research Institute, University of Adelaide, Adelaide, Australia
[2] ARC Industrial Transformation Training Centre for Innovative Wine Production, Waite Research Institute, Adelaide, Australia
[3] Consilium Technology Pty Ltd, Adelaide, Australia

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*correspondence:
cassandra.collins@adelaide.edu.au

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ABSTRACT

There is increasing scientific consensus that climate change is one of the underlying causes of the prolonged dry and hot conditions that have increased the risk of extreme fire weather in many countries around the world. In December 2019, a bushfire occurred in the Adelaide Hills, South Australia, where 25,000 hectares were burnt, and in vineyards and surrounding areas various degrees of scorching and infrastructure damage occurred. The ability to coordinate and plan recovery after a fire event relies on robust and timely data. The current practice for measuring the scale and distribution of fire damage is to walk or drive the vineyard and score individual vines based on visual observation. The process is time consuming, subjective, or semi-quantitative at best. After the December 2019 fires, it took many months to access properties and estimate the area of vineyard damaged. This study compares the rapid assessment and mapping of fire damage using high-resolution satellite imagery with more traditional ground-based measures. Correlations between ground visual fire damage assessments and postfire NDVI (-0.347 to -0.084) and VARIgreen (-0.333 to 0.074) satellite imagery were significant but showed no correlation to a weak negative correlation. Canopy growth, vine fertility and starch concentrations were tracked in the two seasons following the fire event to assess vine recovery. Canopy health in the seasons following the fires correlated to the severity of the initial fire damage. Severely damaged vines had reduced canopy growth, were infertile or had very low fertility as well as lower starch concentrations in buds and canes during dormancy, which reduced productivity in the seasons following the bushfire event. In contrast, vines that received minor-moderate damage were able to recover within 1-2 years. Tools that rapidly and affordably capture the extent and severity of damage over large vineyard area will allow producers, government and industry bodies to manage decisions in relation to fire recovery planning, coordination and delivery, improving the efficiency and effectiveness of their response.

KEYWORDS: scorching, satellite imagery, productivity, vineyard recovery, fertility

INTRODUCTION

Many vineyards around the world are located in regions characterised by persistent hot and dry summers. Warm springs, hot summers, dry vegetation, strong winds and low humidity create the ideal conditions for bushfires (wildfires) (Hantson *et al.,* 2016). While they play an important role in our ecosystems (Lloret *et al.,* 2002), an increase in their occurrence and frequency has been observed in recent years (Westerling *et al.,* 2006; Dutta *et al.,* 2016; Westerling, 2016) and climate change has been linked to fire seasons starting earlier and finishing later, resulting in greater geographic coverage and duration, intensity, as well as economic and social impacts (Westerling, 2016, Jolly *et al.,* 2015).

Despite the increase in bushfires, there is relatively little research on their impacts on grapevines and studies have largely concentrated on the analysis and/or amelioration of smoke taint in grapes and wine (Kennison *et al.*, 2007; Ristic *et al.,* 2011; Wilkinson *et al.*, 2011; De Vries *et al.*, 2016; Fuentes *et al.*, 2019; Ristic *et al.*, 2016; van der Hulst *et al.,* 2019; Mirabelli-Montan *et al.,* 2021). However, in some cases, vineyards have been subjected to fire damage and very little is known about their growth and recovery after this occurrence. Hamilton (2020) outlines the practical considerations when assessing fire damage and planning for vineyard recovery. Scarlett *et al.* (2011) assessed vineyard viability using visual assessments of leaf damage and cordon, trunk, and latent bud tissue viability after the 2009 fires in Victoria, Australia. They concluded that multiple assessment methods were required to rapidly and accurately capture fire damage. A study of vine recovery (Pinot noir and Semillon) after a bushfire in 2008 in South Australia reported that vines with visual symptoms of fire-damage had lower yields in the following season but made nearly a full recovery by the second season (Collins *et al.,* 2013). Lower yields were attributed to reduced fruitfulness and bunch weight (lower berry numbers per bunch). However, fire damage to this vineyard was isolated to areas on the vineyard boundaries near the surrounding trees. To better understand vine recovery after a fire a greater range in fire damage should be investigated.

One of the challenges with studying fire damage in vineyards is that the intensity of fire can vary considerably across a vineyard or a block of vines, as illustrated in previous articles (Wilkinson and Collins, 2010; Scarlett *et al.,* 2011; Collins *et al.,* 2013; Hamilton, 2020). The trauma and competing recovery interests following fire events make it difficult for growers, industry bodies and government to rapidly assess the level of damage incurred. This information is critical in developing effective recovery plans in the short and medium terms for all stakeholders.

In December 2019, a bushfire event occurred in the Adelaide Hills, South Australia where 25,000 hectares were burnt and caused various degrees of scorching and infrastructure damage in vineyards and surrounding areas. Ground truthing damage to 1100 hectares of vineyards following this fire event was labour intensive, taking months to complete. Additionally, only a small sample of each vineyard was assessed and used to estimate the total damage across each property. Delays in assessment meant that true estimates of damage were difficult to accurately calculate due to the regrowth of vines and the vineyard floor area.

Numerous studies recommend the use of satellite data as a more cost-effective tool to assess agricultural damage (De Leeuw *et al.*, 2014; Black *et al.*, 2016; Bokusheva *et al.*, 2016). To overcome the challenge of rapid and accurate assessment after fire damage, satellite imagery may be a good solution, particularly vegetation indices (Cunha *et al.*, 2010; Devaux *et al.*, 2019; Khaliq *et al.*, 2019; Cogato *et al.*, 2020). NDVI is a commonly used vegetation index which makes use of the red and near infrared bands. It has been used in studies relating to canopy growth and vigour (Xue and Su, 2017) and was found to be the most commonly used vegetation index in viticulture publications (Giovos *et al.,* 2021). VARIgreen (often referred to as just VARI) was designed to be less sensitive to atmospheric conditions than NDVI (Gitelson *et al.,* 2002). Although, it was initially developed on corn and wheat crops, it has been used successfully in vineyard studies previously (Cogato *et al.,* 2021; Giovos *et al.,* 2021) and was investigated in this study.

As such, the aims of this study were to (1) Investigate if satellite imagery can rapidly and objectively map fire damage; and (2) Understand the relationship between fire damage and the long-term viability and productivity of damaged vines. It was hypothesised that satellite imagery would correlate with ground truth data and that vine recovery would vary depending on the initial fire damage. A gain in knowledge in this area will provide growers with a better understanding of the likely effect of fire damage on vine health and productivity to improve vineyard management after a bushfire.

MATERIALS AND METHODS

1. Vineyard sites and experimental trial design

Ten vineyard sites across the Adelaide Hills region that were damaged in the fire were selected for this study. Selection of sites was based on the owners' willingness to participate and varying degrees of fire damage across the block. These vineyards were assessed for initial fire damage and vine recovery was monitored over a period of two years from February 2020 to March 2022. Details on the vineyard sites selected in the study are shown in Table 1.

2. Fire damage

2.1. Fire damage assessments

Visual ground assessments of fire damage were made in February/March 2020 for Blocks A-E and for Blocks F-J in early April 2020. As these assessments were made 2-4 months after the fire it was difficult to separate minor and moderate fire damage due to some shoot regrowth. As such, three classifications were used to categorise fire damage; severe, minor-moderate and no visible damage (Figure S1).

TABLE 1. Site details of selected vineyards for the assessment of initial fire damage and vine recovery.

Site details	Variety	Block size (Ha)	Pruning method	Visual ground assessment of damage
A	Prinot gris	1.1	Spur	All vines assessed and three zones of fire damage
B	Sauvignon blanc	2.1	Cane	All vines assessed and three zones of fire damage
C	Chardonnay	1.4	Cane	All vines assessed and three zones of fire damage
D	Sauvignon blanc	0.7	Cane	All vines assessed and three zones of fire damage
E	Sauvignon blanc	0.7	Cane	All vines assessed and three zones of fire damage
F	Pinot noir	1	Spur	Three zones of fire damage*
G	Pinot noir	1.1	Spur	Three zones of fire damage
H	Chardonnay	8.8	Spur	All vines assessed and three zones of fire damage
I	Pinot noir	0.8	Spur	Three zones of fire damage
J	Pinot noir	1.4	Spur	Three zones of fire damage

*Three zones of 12 vines per zone, classified as severe, minor-moderate and no visible damage were selected for detailed assessment.

Ground visual assessments were carried out on every vine at six of the ten sites after the fire event (Sites A-E and J). Due to the resources available for the research study it was not possible to undertake assessments of every vine, at every site for all measurements. Therefore, three damage zones (12 vines per damage zone) at all ten sites were selected and represented the three categories of damage; severe, minor-moderate and no visible damage.

2.2. Conversion of ground truth data to geospatial format

In order to convert ground truth data to a geospatial format, fire damage classes were assigned to each point based on the raster images (as explained at Step 5). The output from each of the steps in the fire damage data conversion process described below can be seen in Figure S2.

▸ **Step 1 - Draw vine rows:** Damage levels presented were based on a vine row and vine number without a geographic location. This was performed for blocks A-E and J as a vine fire damage assessment was completed on every vine in these blocks. . Vine rows were drawn in QGIS Geographic Information System (QGIS Association, http://www.qgis.org, Version 3.16.10) by the creation of a shapefile of vine rows (Figure S2). The following plugins were used; Borys, Jurgiel, 2020, Point Sampling Tool, version 0.5.3. https://github.com/borysiasty/pointsamplingtool. The vine rows are drawn based on Google Satellite Hybrid tiles within QGIS imported as a XYZ connection (https://mt1.google.com/vt/lyrs=s&x={x}&y={y}&z={z}).

▸ **Step 2 - Generate equally spaced vine points:** In order to geolocate each vine, the assumption was made that the vines were equally spaced along each vine row. Thus, the correct number of vines per row was generated to be equally spaced along the vine rows.

▸ **Step 3 - Assigning damage classes:** In this step, the damage class was assigned to the vine points generated in Step 2. This step also included the correction of all class notions to be consistent with those found in Figure 1; red = severe damage, yellow = minor to moderate damage, blue = no visible damage and black = missing.

▸ **Step 4 - Convert points to raster:** The above points were converted to raster by means of nearest neighbour in order to facilitate later comparison with satellite imagery. This maintained the classes as determined in Step 3 while assigning the pixels the class value from the closest point. The same colour scheme was used to match those used for Step 3.

2.3 Comparison of ground truth data and satellite imagery

The satellite imagery procured was both orthorectified and atmospherically corrected by the provider (MAXAR) through their GBDX platform and supplied as reflectance. Details of satellite imagery type and date of capture are provided in Table S2. The multispectral imagery was pansharpened and georeferenced to best align with the Google tiles used to draw the vine rows.

The imagery considered in this paper is a subset of a larger set of imagery used and due to the varying resolutions, all imagery for which there was complete vine by vine fire damage was resampled to 0.5 m post georeferencing. This was done using bilinear resampling. While not ideal to lose resolution across many of the images, for the purposes of the models that were planned for consideration, it was necessary for all the images to be of the same resolution. This was done post georeferencing in order to minimise the effects of the down sampling on georeferencing.

To compare ground truth data and satellite imagery the correlation coefficient was calculated between ground truth fire damage data and post fire Normalised Vegetation Index (NDVI) and Visible Atmospherically Resistant Index Green (VARIgreen) (Gitelson *et al.*, 2002; Cogato *et al.*, 2021; Giovos *et al.*, 2021). As some of the imagery used in this study consists of only red, green, blue and near infrared bands, VARIgreen's use of the red, green and blue bands is appealing as it makes use of the majority of the available spectrum coverage.

The following equation is used:

$$VARIGreen = \frac{Green - Red}{Green + Red - Blue}$$

As the fire damage is ordinal Spearman's Rank Correlation Coefficient was used. As with other correlation coefficients, it lies between -1 and 1, where -1 denotes a perfect negatively monotonic relationship and 1 denotes a perfect positively monotonic relationship. In order to avoid the inclusion of mid row and field edges, it was decided to work with point data sampled from the satellite imagery rather than the image as a whole. However, as some misalignment may still be present post georeferencing and as we have estimated the locations of the vines along a row as equally spaced, a buffer was created around each point of 1.5 x 1.8 m. This buffer was implemented as either 1.5 x 1.8 m or 1.8 x1.5 m depending on vine row orientation to maximise the buffer in the along line direction while minimising the buffer in the between vine direction. The buffer was chosen to be this size in order to try minimise mid-row inclusion while maximising the inclusion of vine row. Pre- and post- fire satellite imagery captured on 18th December 2019 and 28th/29th December 2019 respectively was used for comparison. Site C was the exception, with post-fire satellite imagery captured on the 29/02/2020.

3. Vine recovery - canopy growth, vine fertility and starch concentration

To assess vine recovery in the seasons following the fire event, canopy growth, vine fertility and starch concentration of bud and cane tissues were assessed in the 2020/21 and 2021/22 growing seasons.

3.1. Canopy growth assessments

The VitiCanopy app was used to capture upward looking images of grapevine canopies and calculate Plant Area Index (PAI) using the method described in De Bei *et al*. (2016). Canopy assessments were made at each site at 3-5 time points (COVID-19 restrictions limited access at some sites) during the 2020/2021 growing season and 5 time points in the 2021/2022 growing season. Due to the level of fire damage and productivity of the vineyard area, owners made the decision to remove vines at site G in 2020/21 and sites I and J in 2021/22. As such, measures were not recorded for these sites after vine removal. Assessments were made at each of the selected zones of damage (severe, minor-moderate and no visible damage) to monitor canopy growth over time.

3.2. Vine fertility assessments

Vine fertility was evaluated at two developmental stages over two seasons following the fire event; winter dormancy via bud dissection analysis to assess bud fertility and at harvest via the assessment of yield components.

Bud fertility assessments were made on canes collected from all sites; 30 canes per fire damage zone. Compound buds at node positions 1-4 at spur pruned sites and node positions 1-10 at cane pruned sites were dissected using a razor blade to make transverse cuts through the bud axes as described in Rawnsley and Collins, 2005. The bud was then observed under a light microscope at 25x magnification (Model EZ4W, Leica, Heerbrugg, Switzerland). The number of inflorescence primordia (IP) in the primary bud of each compound bud was recorded. If the primary bud was necrotic, the largest secondary bud was assessed instead (assumption that secondary bud would compensate for the loss of the primary bud). Images of dissections were taken using the Leica AirLab App, and the cross-sectional area of IP (IA) was measured on the images using software Image J (NIH, USA).

Yield components; bunch number per shoot, bunch weight, berry number per bunch and berry weight were measured at harvest on 12 vines from each fire damage zone at each site in growing seasons 2020/21 and 2021/2022 (except where vineyards were removed or reworked).

3.3. Starch assessments

During winter dormancy samples of canes and buds were collected from vines at each site from each of the fire damage zones in both the 2020/21 and 2021/2022 growing seasons. All samples were kept on dry ice until storage in a -80 °C freezer and then freeze dried (Alpha 2-4 LSC; John Morris Scientific, Adelaide, Australia). For starch analysis, bud and cane samples were ground in an electrical mill (Model A11, IKA, Germany). Starch analysis was performed using a commercial enzyme assay kit (Total starch assay kit, Megazyme, Ireland) following the method described in Edwards *et al.* (2011). Using a spectrophotometer (Multiskan Spectrum, model 00300011, Thermo Electron Corporation, Vantaa, Finland) the absorbance was read at 505 nm and the starch content determined using a glucose standard curve.

4. Statistical analysis

Fire damage comparisons, seasonal effects and the interaction of the two (fire damage x season) were analysed via two-way ANOVA; means were then separated using the Tukey's test. Where vines were removed after the first season and for PAI assessments, a one-way ANOVA was performed. XLSTAT® (Version 2022.1.1 Premium 1248, Addinsoft SARL, Paris, France) was used for all statistical analyses. Means were separated at a significance level of $p < 0.05$ for all data.

RESULTS

1. Fire damage assessment comparisons

The percentage damage based on ground visual assessments is presented in Table S1. To spatially visualise the fire damage at the ten sites pre- and post- fire satellite imagery was generated with ground truth sampling raster and pre- and post- fire NDVI and VARIgreen imagery and is presented in Figures 1 and 2 and Figure 3 (no ground truth data at block level).

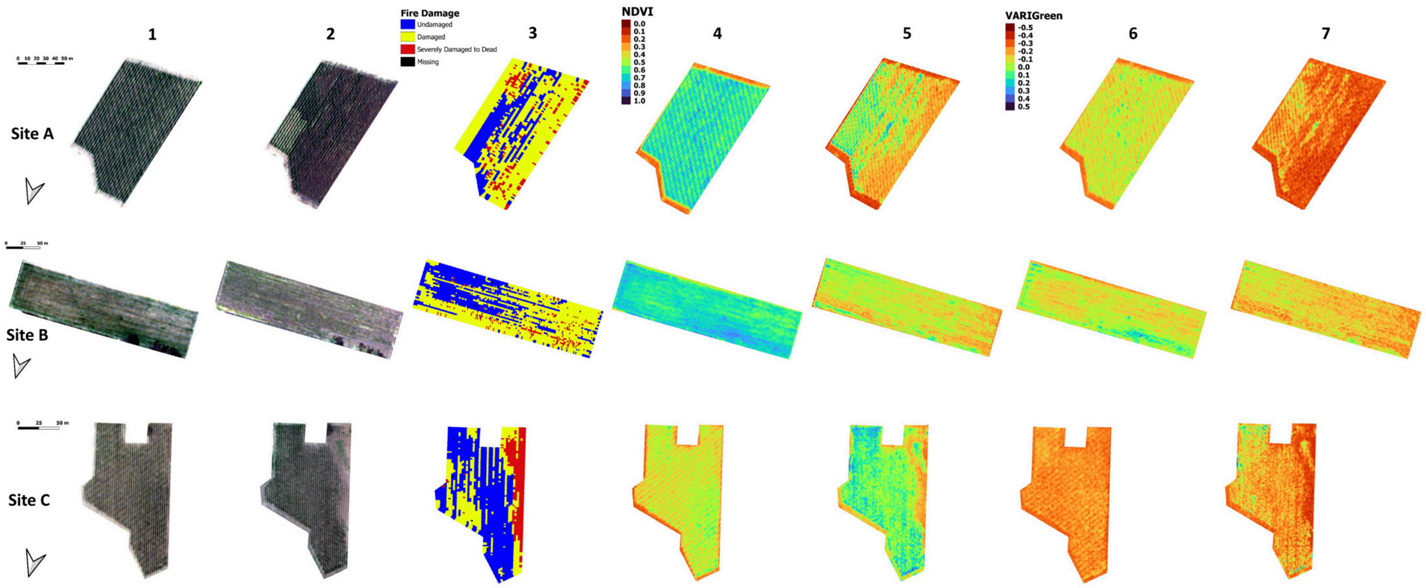

FIGURE 1. Pre- and post- fire satellite imagery (1,2), ground truth sampling raster (3), pre- and post- fire Normalised Difference Vegetation Index (NDVI) imagery (4,5) and Visible Atmospherically Resistant Index Green (VARIgreen) imagery (6,7) of sites A, B and C, Adelaide Hills, South Australia. The ground truthing colours are red, yellow and blue to indicate severe, minor-moderate damage and no visible damage; black indicates missing vines.

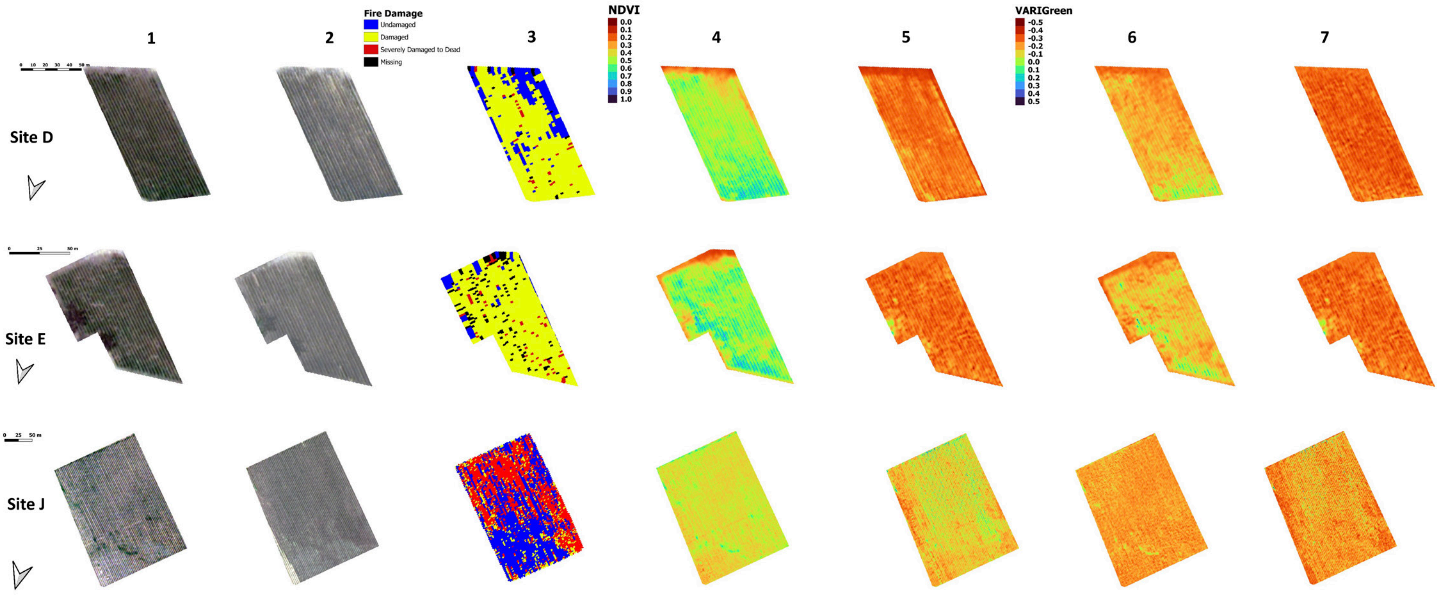

FIGURE 2. Pre- and post- fire satellite imagery (1,2), ground truth sampling raster (3), pre- and post- fire Normalised Difference Vegetation Index (NDVI) imagery (4,5) and Visible Atmospherically Resistant Index Green (VARIgreen) imagery (6,7) of sites D, E and J, Adelaide Hills, South Australia. The ground truthing colours are red, yellow and blue to indicate severe, minor-moderate damage and no visible damage; black indicates missing vines.

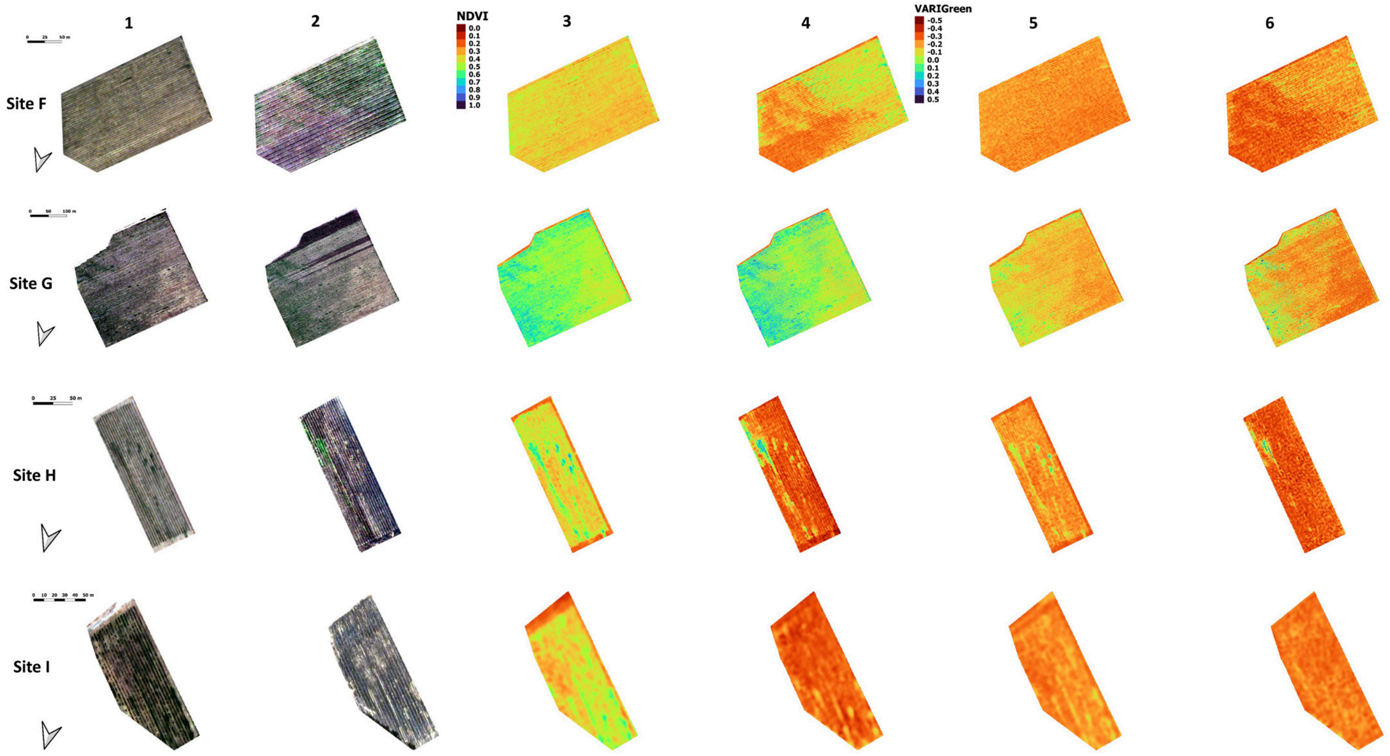

FIGURE 3. Pre- and post- fire satellite imagery (1,2), pre- and post- fire Normalised Difference Vegetation Index (NDVI) imagery (3,4) and Visible Atmospherically Resistant Index Green (VARIgreen) imagery (5,6) of sites F, G, H and I, Adelaide Hills, South Australia.

TABLE 2. Spearman's Rank coefficients of correlations between ground fire damage assessments NDVI and VARIgreen indices.

Site	Ground assessment and NDVI correlation	p-value	Ground assessment and VARIgreen correlation	p-value
A	- 0.334	< 0.0001	- 0.305	< 0.0001
B	- 0.338	< 0.0001	- 0.333	< 0.0001
C	- 0.347	< 0.0001	- 0.074	< 0.0001
D	- 0.119	< 0.0001	- 0.082	< 0.0001
E	- 0.114	< 0.0001	0.077	< 0.0001
J	- 0.084	< 0.0001	- 0.307	< 0.0001

NDVI - Normalised Difference Vegetation Index and VARIgreen - Visible Atmospherically Resistant Index Green.

The greatest vine damage due to fire was observed at site J which can be seen when comparing pre- and post-fire satellite imagery and ground truth assessments (Figure 2, Table S1) where over 75 % of the vineyard displayed visible signs of damage. Sites D and E were scored as having over 80 % and 89 % damage respectively but most of this was minor to moderate fire damage. At sites A-C the three classifications of fire damage are better represented. A greater proportion of vines assessed as having no visible signs of damage; 26 %, 33 % and 55 % respectively and a higher proportion of severely damaged vines compared to other sites; 9 %, 6 % and 14 % respectively (Table S1). Post-fire satellite imagery, ground truth sampling raster and NDVI and VARIgreen imagery sites A-C are similar (Figure 1), although relatively weak, the correlations presented in Table 2 support this observation. The negative correlation is expected as increasing fire damage should result in a lower NDVI and VARIgreen, as these increase in value with better plant health. The opposite was observed for sites D, E and J (Figure 2) where post-fire NDVI and VARIgreen imagery did not correlate well with ground truth assessments (Table 2). Pre- and post-fire damage differences can be seen between sites F-I but as no site level ground assessments were made due to vineyard access it was not possible to perform correlations.

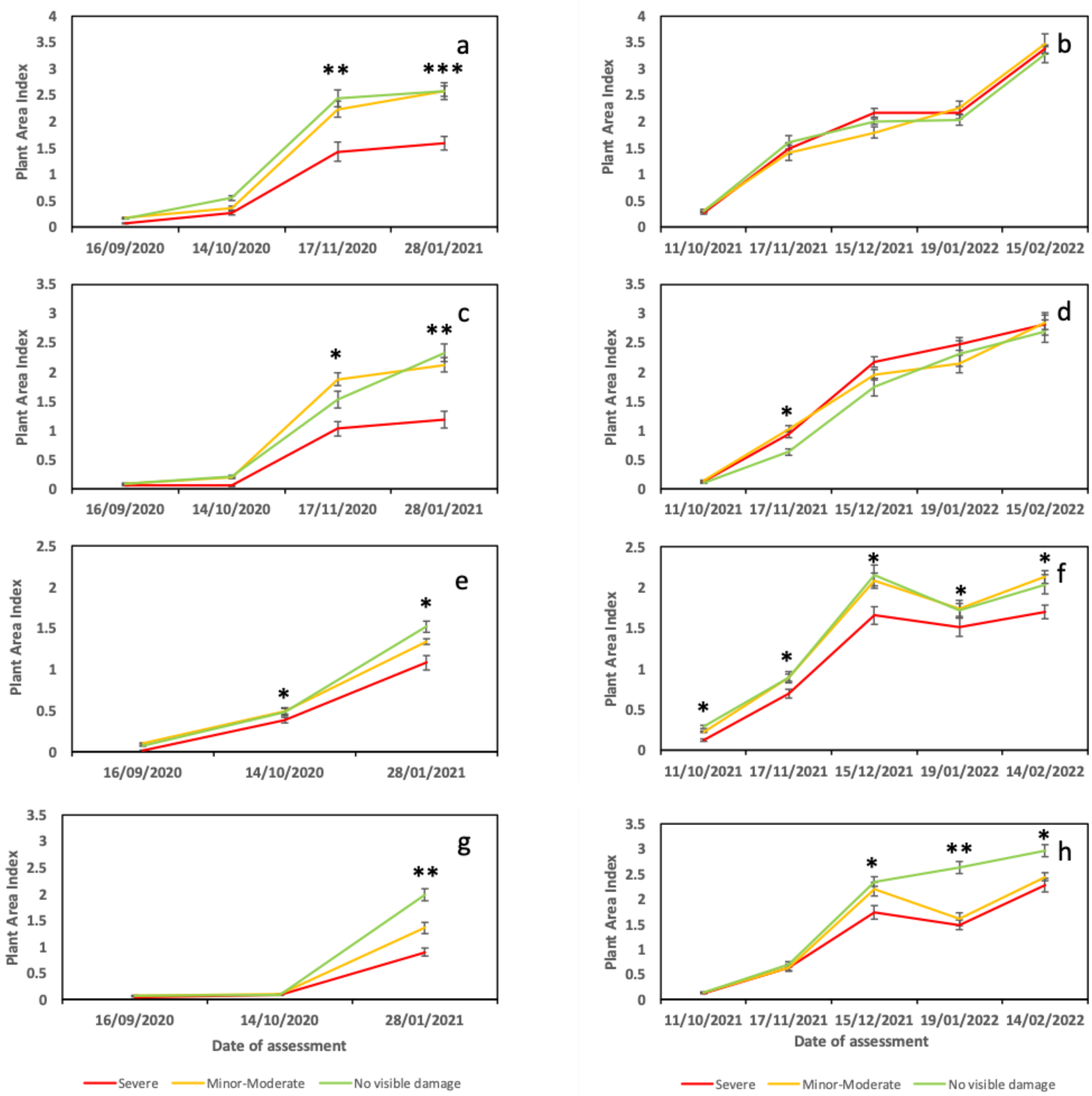

FIGURE 4. Plant Area Index measures of three different fire damage classifications; severe, minor-moderate and no visible damage at sites A (a and b), B (c and d), C (e and f) and D (g and h) from the 2020/21 and 2021/22 growing seasons, Adelaide Hills, South Australia.

Fire damage classifications were analysed using one-way ANOVA. Each data point is a mean of n=12 vines. Bars indicate the standard error. *, ** and *** indicate significance at $p \leq 0.05$, 0.01 and 0.0001 respectively, using the LSD test at 5 % level.

2. Canopy Growth

To assess and monitor vine recovery, canopy growth was measured as PAI during the two seasons following the fire event (2020/21 and 2021/22) (Figures 4 and 5). In the first season (2020/21) after the fire, severely damaged vines at all sites, apart from site H had lower PAI at later stages of canopy development compared to those where no visible damage was observed. Vines classified as having minor-moderate fire damage had similar PAI at sites A, B, E, F, J to vines with no visible damage, while at site I, PAI values were similar to severely damaged vines and relatively low compared to other sites.

PAI values at sites A and B in the second season (2021/22) were not different between any of the fire damage classifications. However, at site C only minor-moderately damaged vines had similar PAI levels to vines where no visible damage was observed. At sites D-F PAI for both minor-moderate and severely damaged vines was lower than no visible damage vines. Whereas at site H, no differences in PAI were observed between fire damage classifications at any time points in the two seasons following the bushfire.

3. Vine fertility and starch concentration

Seasonal differences in fertility were observed at some sites (Figure 6, Tables S3-5). Fruitfulness was higher in the second

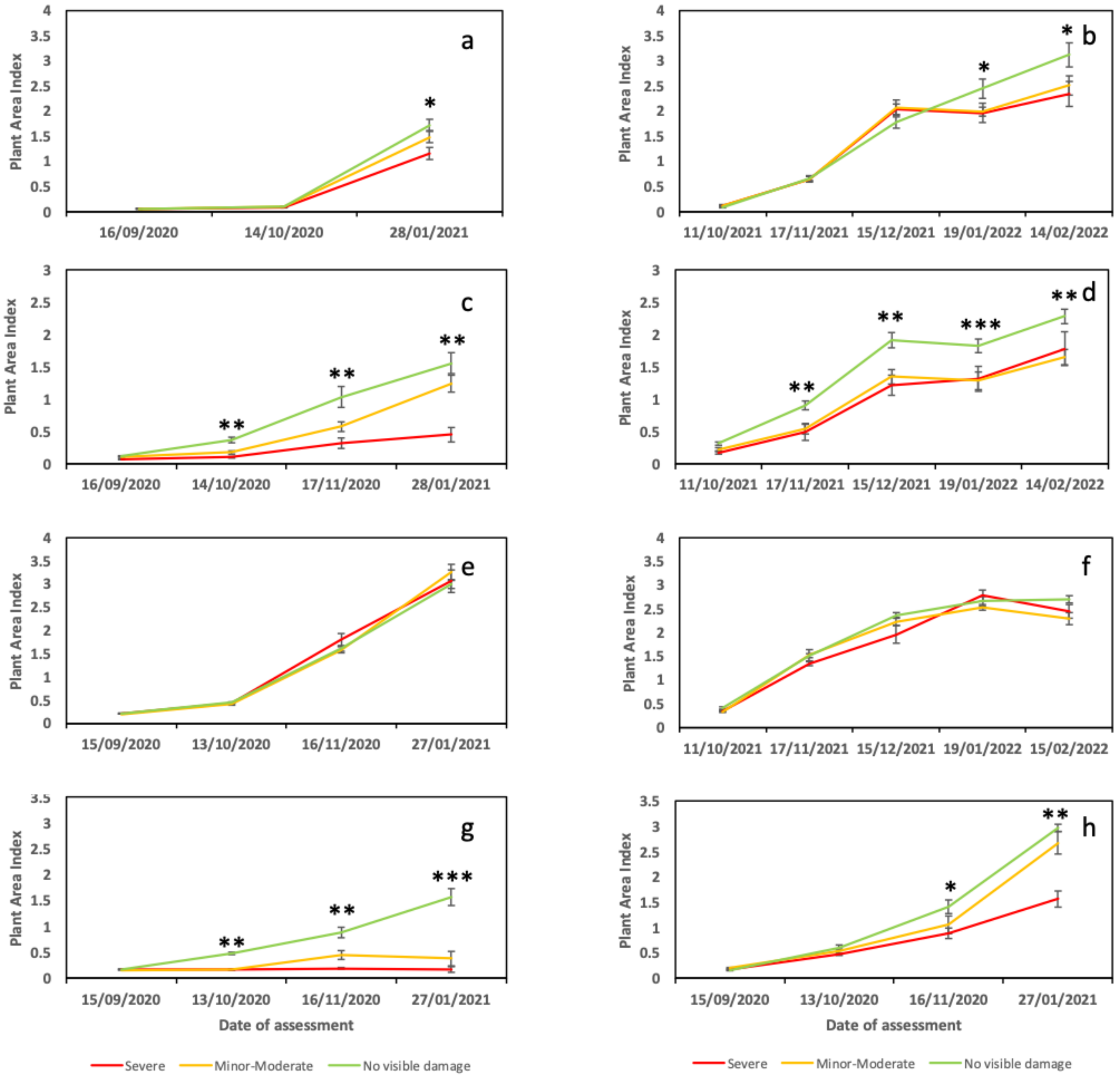

FIGURE 5. Plant Area Index measures of three different fire damage classifications severe, minor-moderate and no visible damage at sites E (a and b), F (c and d) and H (e and f) from the 2020/21 and 2021/22 growing seasons and sites I (g) and J (h) from the 2020/21 growing season (vineyards removed after first season), Adelaide Hills, South Australia.

Fire damage classifications were analysed using one-way ANOVA. Each data point is a mean of n = 12 vines. Bars indicate the standard error. *, ** and *** indicate significance at p ≤ 0.05, 0.01 and 0.0001 respectively, using the LSD test at 5 % level.

season at sites B-F (Tables S3 and S4). IA was higher in the second season at sites A and D and lower at sites B and H, while bunch weight was lower in the second season at A, F and H and higher at sites D and E. Both berry number per bunch and berry weight were lower in the second season at sites A and F. While berry weight was lower at site H. Higher berry numbers per bunch were observed at sites B-D and E in the second season and berry weight at sites C and F (Table S5).

Vine fertility followed a similar trend to canopy growth (PAI) where fertility was reduced after fire damage, but at most sites recovery was seen in the second season (Figure 6 (a,c,e,g), Tables S3-5). Clear differences in inflorescence number between fire damage classes were observed at sites C, F and I with higher IP number and greater IA for buds collected from no visible damage vines, followed by minor-moderate and then severe damage. At sites A, B, D and E, IP and IA were lower only for severely damaged vines and at sites G and J both minor-moderate and severely damaged vines had similar IP and IA values (Table S3). No differences in IP, IA, and bunch number per shoot were observed between levels of fire damage at site H; only bunch weight was lower for severely damaged vines in the first season.

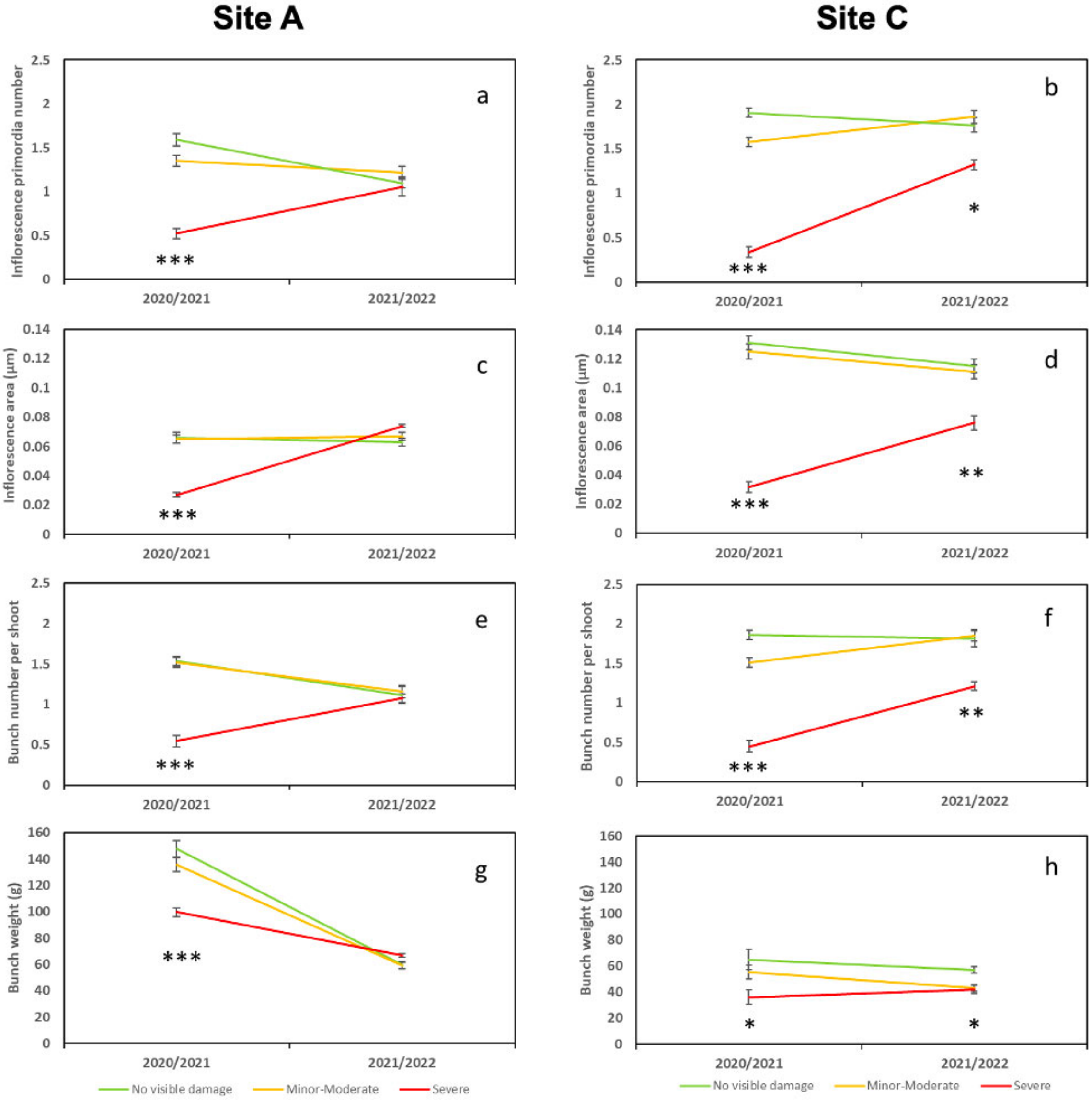

FIGURE 6. Inflorescence primordia number (a and b), inflorescence area (c and d), bunch number per shoot (e and f) and bunch weight (g and h) measures of three different fire damage classifications; severe, minor-moderate and no visible damage at Sites A and C in the 2020/21 and 2021/22 growing seasons Adelaide Hills, South Australia.

Fire damage classifications were analysed using one-way ANOVA. Each data point is a mean of n = 12 vines. Bars indicate the standard error. *, ** and *** indicate significance at $p \leq 0.05$, 0.01 and 0.0001 respectively, using the LSD test at 5 % level.

Bunch number per shoot and bunch weight aligned with IP and IA values at most sites (Table S4). Bunch number at sites A-D and bunch weight at A and F were not different between fire damage classes. Lower bunch weight, berry weight and berry number per bunch were observed in severely damaged vines at sites B and C in both seasons (Tables S4 and S5). In the first season, berry number per bunch was lowest in severely damaged vines at sites, A-C and J and berry weight at sites B-E, I and J. By the second season only lower berry weight was observed for severely damaged vines at site B and berry number per bunch at site C.

Bud and cane starch levels were higher in the second season for all sites apart from sites where vines were removed (Table S6). Cane starch was not different at sites A and H between fire damage classes (Table S6). Lower cane starch levels were observed in severely damaged vines at sites B-G, I and J in the first season and at sites C-F in the second season. While bud starch levels were lower in the first season at most sites (A-C, F, G, I and J) and at sites A-D in the second season. Minor-moderately damaged vines had lower bud starch levels at site D in the first season. Bud starch levels did not vary between fire damage classes at site H (Table S6).

DISCUSSION

In order to be able to make decisions regarding how best to manage vines after fire exposure, it is important to understand the effects on the long-term viability of exposed vines. The first step to this process is to appreciate that fire exposure can vary significantly between vineyards due to the fire intensity

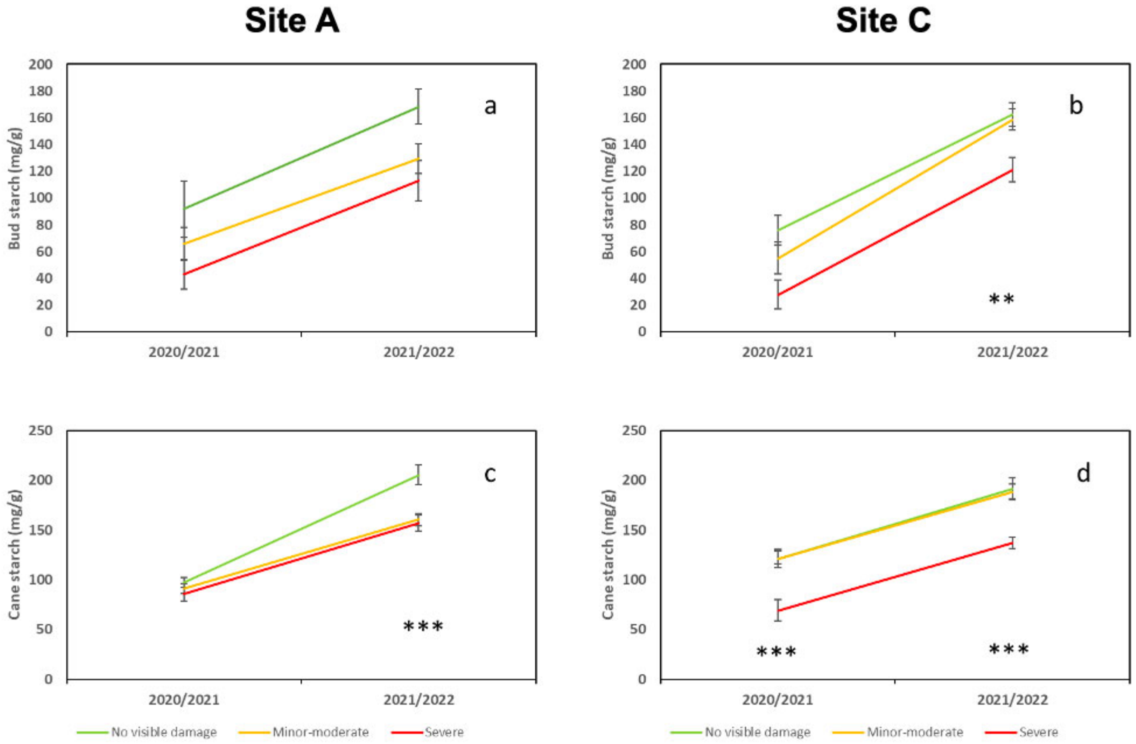

FIGURE 7. Bud starch content (a and b) and cane starch content (c and d) of three different fire damage classifications; severe, minor-moderate and no visible damage at Sites A and C in the 2020/21 and 2021/22 growing seasons Adelaide Hills, South Australia.

Fire damage classifications were analysed using one-way ANOVA. Each data point is a mean of n = 12 vines. Bars indicate the standard error. *, ** and *** indicate significance at p ≤ 0.05, 0.01 and 0.0001 respectively, using the LSD test at 5 % level.

and exposure time to the fire itself or the radiant heat (Scarlett *et al.,* 2011). This is obviously difficult to assess as it is happening and we tend to assess after the fire event has stopped and when it is safe to enter the vineyard. The next step is to assess the level of damage that has occurred not only to the vines but also to the infrastructure (e.g., trellis and irrigation system) to calculate the damage and prioritise management activities going forward (Hamilton, 2020). Typically, the severity of vine damage is classified into groups and based on a visual assessment (Whiting, 2012; Scarlett *et al.,* 2011, Hamilton, 2020). In this study, three categories were chosen and described as 'no visible damage', 'minor-moderate' and 'severe' damage as shown in Figure S1. No more than three categories were chosen as it was very difficult to separate minor and moderate damage between vines, as there was relatively large variation between vines within these categories, which has also been reported by Scarlett *et al.* 2011 and Hamilton 2020. Without conducting viability assessments on every vine it was also difficult to separate severely damaged vines and those that were dead so for this study they were grouped together in initial assessments. Variation in damage can be due to a number of reasons such as partial burns to vines, where the fire only burns one side of the vine as it moves through the vineyard, fire intensity differences due to different vineyard floor management such as vegetation and mulches, proximity to surrounding trees and types of surrounding vegetation (Whiting, 2012).

Within the ten sites chosen for this study there was a range of different levels of fire damage. Damage ranged from very little at site H to high levels of damage at site J (Figures 1 -3 and Table S1). The satellite imagery captured and presented in this study demonstrates these differences are more obvious at some sites compared to others. Pre- and post- satellite fire imagery at sites A-C, H and J showed clearer patterns of fire damage compared to sites D-G, and I. When comparing the coefficients of correlations between ground truth data and vegetation indices, A-C and H showed greater correlation with ground data, although still relatively weak. Normalised Difference Vegetation Index is the standard baseline vegetation index (Giovos *et al.,* 2021), however, it only uses the red and near infrared bands. While, VARIgreen combines information from more bands (red, green and blue) and was included to investigate if coefficients of correlation improved with the inclusion of more bands. It is important to note that these correlations are only indicators of a relationship for these very specific indices and are not indicative of the results that would be expected from a machine learning model trained on all of the bands. As such, a model may find different combinations of bands and/or indices that provide more optimal information regarding the damage state. This will be explored and the focus of future work, following similar strategies as those reported on vineyards affected by frost (Cogato *et al.,* 2020; Li *et al.,* 2021).

After fire damage, vines have the ability to recover with time, however there are consequences in terms of canopy growth and development, vine fertility and starch reserves. The ability to recover and the speed of recovery appear to be related to the extent of initial fire damage.

Cold-injury following freezing events elicits a similar response in grapevines (Wolfe, 2001, Keller and Mills, 2007). Canopy growth of vines in the first season following fire damage was consistently lower for vines that were classified as severely damaged at all sites, apart from at site H; which had the least fire damage of all sites. Interestingly, this pattern of growth development aligns with cane starch concentrations which were generally lower for vines that were severely damaged by the fire, particularly in the first season. Again, at site H no differences in cane or bud starch concentrations between fire damage classes were observed. As starch is known to be the main reserve compound in grapevine storage tissue (Winkler and Williams, 1945) it makes sense that stress inflicted by the fire potentially reduced photosynthetic performance and reserve accumulation, with implications for canopy growth and development and yield in the following seasons (Hunter *et al.,* 1995). Only at sites A and B did the canopy growth fully recover by the second season and at both of these sites, additional water and nutrients were applied to the vines during the recovery phase, compared to other sites that maintained normal management practices. At sites D-F, both the vines classified as minor-moderate and severely damaged had lower PAI compared to those with no visible damage. While at site C it was only severely damaged vines that had a lower PAI. These patterns also align with overall fire damage at each of the sites, as can be seen in satellite imagery presented in Figures 1-3. It may be possible to improve recovery times by adapting viticultural management practices, such as pruning strategies, nutrient regimes and water management (Rose, 2009; Whiting, 2012; Collins *et al.,* 2013; Wang *et al.,* 2019; Hamilton, 2020). Experimental trials comparing different pruning strategies have been established and will be reported in future work.

A decrease in fruitfulness in the first season following the fire was observed at all sites (apart from site H) and particularly for vines that were severely damaged. Grapevine reproductive development occurs over two growing seasons (Iland *et al.,* 2011). It starts at floral induction, followed by initiation and differentiation of inflorescence primordia within buds in the first year, and further development of inflorescence in the second year until reaching bunch maturity (May, 2004). Hence the results found in this study are not surprising as when the fire occurred in December 2019 it coincided with the development of inflorescence primordia in the compound buds on the current season shoots. The conditions during the initiation and differentiation of IP in the current season are known to influence bud fruitfulness and potential yield (Li-Mallet *et al.,* 2016). In addition, a vine reserves during development can influence bud fruitfulness as the actively growing shoot tips, young leaves and inflorescences strongly compete for reserves with the compound bud (Buttrose, 1966; Candolfi-Vasconcelos and Koblet, 1990). Hence, IP initiation and differentiation can be suppressed by limited reserves. This is supported by lower bud and cane starch levels reported in this study, particularly for severely damaged vines in the first season. Lower berry number per bunch and berry weights were observed and may also be attributed to the reserve status of the vines (Hunter *et al.,* 1995). At all sites starch levels were higher in the second season (where measured) suggesting that strategies to improve storage accumulation in vines may be an important management approach to consider in order to shorten the recovery time.

Unfortunately, the interactions between fire severity/damage and vine recovery are still poorly known, especially at the scale of a large fire. Remote sensing imagery has been used to study the influence of fire severity on vegetation recovery (Díaz-Delgado and Pons, 2001; Díaz-Delgado *et al.,* 2003). Correlation between post fire NDVI and VARIgreen with fire damage was assessed as a first initial exploratory data analysis task due to the potential for delay in the fire damage assessment. Additional analysis such as considering the NDVI difference pre and post fire would likely be a better indicator of later model performance. Additionally, it is acknowledged, that considering a time series approach of the NDVI or other indices over several years for the same area at a similar time may well help define the 'normal' state of the particular vineyard block under consideration. The current approach also does not account for natural variability within the vineyard block. Due to variability in pre-fire NDVI, the assessment has been performed at the block level although if the difference in NDVI had been used, merging of the data from all blocks could have been considered. Satellite imagery tracking vineyard recovery in the seasons following the bushfire is also currently being correlated to field assessments of vineyard productivity such as canopy health and development, fertility and starch concentration and will be reported in a future publication. Studies by Cogato *et al.,* 2021; Pinel *et al.,* 2021; Lopez-Fornieles *et al.,* 2022 are examples of strategies we can use to further explore these relationships.

CONCLUSION

Quantifying the level of fire damage in vineyards after a fire event is currently time consuming and as such make accurate assessment difficult over a large area. The use of satellite imagery to overcome these issues was investigated through the comparison of vegetation indices; NDVI and VARIgreen with ground truth measures of damage. However, only weak correlations were found with these two indices and will be explored further using machine learning approaches. In the future, analysis of satellite imagery could also be supported by UAV imagery (Brook *et al.,* 2020).

Tracking vine recovery after a fire is critical to our understanding of the influence of different levels of fire damage on plant health. However, this is challenging as the varying degrees of fire damage are difficult to quantify and were not imposed by the authors, therefore this type of research is more observational (rather than experimental) in nature. This study allows inference to association rather than causation, and authors acknowledge that there may be other contributing factors that were not apparent. Regardless, the large differences in canopy growth and reproductive development between the different levels of fire damage are believed to be of value and interest to producers and managers as they provide some insights into the recovery process that can be used for vineyard management decision making. w

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