Final report

Project title:

Developing management strategies to enhance the recovery of horticulture from bushfires

Project leader:

Bruno Holzapfel

Delivery partner:

New South Wales Department of Primary Industries and Regional Development

Report author/s:

Bruno Holzapfel, Oluyoye Idowu, Tim Pitt*, John Golding, Kevin Dodds, Jessica Fearnley, Paul Petrie*

*South Australian Research and Development Institute

Project code:

AS19002

Disclaimer:

Funding statement:

'Developing management strategies to enhance the recovery of horticulture from bushfires (AS19002)' is funded by the Hort Frontiers Advanced Production Systems Fund, part of the Hort Frontiers strategic partnership initiative developed by Hort Innovation, with co-investment from NSW Department of Primary Industries and Regional Development and South Australian Research and Development Institute and contributions from the Australian Government.

Publishing details:

ISBN <Hort Innovation to add>

Published and distributed by: Horticulture Innovation Australia Limited
ABN 71 602100149

Level 7
141 Walker Street
North Sydney NSW 2060

Telephone: (02) 8295 2300

www.horticulture.com.au

Contents

Public summary

To understand the immediate and long-term effects of bushfires on perennial cropping systems, the 'Developing management strategies to enhance the recovery of horticulture from bushfires' project started in the summer of 2020, shortly after bushfires devastated several horticulture production regions in NSW and SA. The work also aimed to provide information on the best recovery options and to develop strategies to minimise the damage from future bushfires. Although most studies were conducted in apple orchards, the results apply to other horticulture tree crops.

Three monitoring and experimental sites were established in Batlow (NSW). Two were damaged by radiant fire (blow torch) from adjoining vegetation (Rosy Glow and Kanzi™) and one was damaged by smouldering fire (slow cooker; Royal Gala). The Rosy Glow site was also used as a demonstration site with others in the Bilpin area. Damage levels ranged from fire-free to extreme. All experimental sites had six remedial pruning treatments ranging from unpruned (control) to cutting the tree back to the trunk. In addition to remedial pruning, the smouldering fire (slow cooker) site had crop reduction treatments. Two experimental sites were established at Adelaide Hills (SA), in an apple and a cherry orchard, with several pruning treatments applied.

Vegetative and reproductive recovery parameters were collected for 3–4 growing seasons after the bushfire and fruit quality at harvest was assessed. Apple storage and shelf-life performance were monitored for two growing seasons post-fire. Other assessments included perennial tissue non-structural carbohydrate (NSC) levels and tree nutrient status. In a controlled experiment, different heat loads were applied to potted apple trees to represent a smouldering fire, allowing tree assimilation and whole tree NSC balance to be measured.

Apple trees affected by radiant fire had fully recovered by the second growing season post-fire, while trees badly damaged by smouldering fires did not recover and eventually died. This was reflected in NSC levels in roots, which did not differ in trees damaged by radiant fire but declined significantly in extremely smouldered trees in subsequent growing seasons.

As expected, cutting the trees back to the trunk took four growing seasons to attain full canopy recovery. Tree poling was the most efficient and easy-to-implement method for re-establishing damaged orchards and attaining optimum yield, regardless of fire type. The controlled experiment showed how increased heat load in smouldering fires affected apple tree physiology and NSC dynamics by reducing assimilation and NSC root reserves.

This work provides important information on tree recovery strategies and ways to build bushfire resilience in orchards. The work initially resulted in the first in-depth scientific review internationally of the effect of bushfires on horticulture and options to minimise damage from extreme fires that are predicted to increase in frequency. Ongoing communication of project activities and findings was ensured through field days, workshops and seminars. Presentations were given at three international conferences to extend the project outcomes beyond Australia. Finally, a bushfire recovery manual was produced that outlines the initial damage, recovery and options to make horticulture production systems more resilient to bushfires.

Keywords: bushfires; trees; damage; recovery; remediation; resilience; post-harvest; carbohydrates; nutrients; productivity.

Introduction

Severe climatic events such as heat waves and strong winds during the 2019–20 growing season and the effects of prolonged drought led to substantial bushfire damage in apple orchards and other tree crops (e.g. cherries, olives and macadamia) in Australia. The most pronounced effect on longer-term production losses was in apple orchards near Batlow in NSW and the Adelaide Hills in SA. Batlow is where most of the apples are produced in NSW, while the Adelaide Hills is the most significant production region for SA's pome fruit and cherry industries. Teams from NSW Department of Primary Industries and Regional Development (NSW DPIRD) and South Australian Research and Development Institute (SARDI) completed the project, combining expertise in tree physiology, post-harvest physiology and crop production systems, coupled with strong linkages to the industry.

The initial bushfire damage assessment showed great variation between orchards. Often a significant proportion of the orchard was damaged due to the proximity of burning native vegetation or pine tree plantation, which produced a radiant or 'blow torch' fire (Dodds 2020). Dry vegetation under the trees created a smouldering 'slow cooker' burn (Dodds 2020), which caused considerable damage to the trunk and phloem. It was not clear whether the trees would recover from this damage.

Due to the potential short and long-term effects of fire on tree productivity, several observation and management trials were conducted. While these were focused on apples, the results are relevant to other tree crops. First, the potential for damaged trees to recover was assessed. Second, we explored strategies for recovery to full production and in the shortest possible time.

This area of research is novel for any horticultural crop and has limited linkages to other projects. Relevant work, which provided support for the current study, is related to biennial bearing and tree nutrition research and included two past projects: 'Physiological, metabolic and molecular basis of biennial bearing in apple' (AP15013) and 'Improved tree and fruit nutrition for the Australian apple industry' (AP14023). Other related projects include a NSW DPIRD project on the climate vulnerability of perennial crops (horticulture node) and collaborative projects on smoke taint in wine. SARDI has also completed projects in related areas through the Australian Wine Research Institute (AWRI).

While there have been some observational studies on grapevines, avocados and other fruit trees (Collins et al. 2014; Bender 2012; Grills 2009), one publication described the effect of fire on forest tree physiology (Bär et al. 2019). Another paper focused on direct bushfire damage to grapevines and indirect smoke taint in grapes and wine (Krstic et al. 2015). The current study aimed to understand the effects of bushfires on other horticultural production systems, such as apples and cherries.

Destruction of the vascular system by smouldering fire is challenging for tree recovery. Supplying assimilate to the roots is essential and depends on phloem transport, which can be disrupted by the damage to the vascular tissues. The severity of visible and non-visible damage determines the recovery options for an orchard, which could include managing crop loads with pruning and training options, or removing trees and replanting. Measures that will enhance tree sap flow, such as treating the trunks with protective coatings to make them less vulnerable to other extremes (e.g. cold temperature or radiation), could be viable options for recovery.

Investigating how fire-affected trees should be managed is imperative for understanding the best recovery options to achieve full production levels quickly and ensure optimal economic returns. Replanting combined with measures to make orchards more resilient could minimise the damage from future bushfires. By assessing the short- and long-term effects of bushfires on orchards, the appropriate management options can be developed, ultimately leading to orchards that are better prepared for similar events. Improving our understanding and ability to detect the underlying symptoms in fruit and trees are essential for making informed decisions about the subsequent fruit marketability and tree recovery. This project aimed to produce new knowledge about managing fire-damaged orchards and promoting more resilient production systems, then documenting this in a practical manual for growers.

Methodology

Visits to the Batlow and Bilpin regions in February 2020 allowed early observations and initial discussions with the industry. During the project development phase, discussions occurred with SARDI. This was followed by determining potential monitoring and experimental sites to assess the effect of the fires on trees and recovery, including management options. The post-harvest work was started immediately to determine the effects of fire damage on fruit at harvest and during storage. In parallel, a review of the literature showed there was very limited information on the effect of bushfires on horticulture production systems.

Monitoring trials in NSW

Two demonstration sites were established in Bilpin (NSW). The first site looked at recovery after a blow torch fire and the management techniques the grower implemented to bring the trees back to full production. Two orchard walks were held at this site during the early stages of the project for growers to discuss recovery options. This demonstration site was used by project staff as a prop for discussion with apple growers and producers of larger project concepts. The second site was a case study with a grower whose orchard was damaged by a slow cooker fire. This grower pulled out his orchard and replanted it with cherries after the first year of the project and the site was no longer used.

Three monitoring sites were established in the Batlow region (NSW) to provide information on tree recovery from different levels of fire damage, ranging from severe to unaffected trees. The basis for tree selection depended on the type of fire and the damage to the trees. The blow torch fire created a gradient of leaf and fruit damage that moved inwards from the bordering vegetation of the orchard. The slow cooker fire caused a different severity of trunk and lower branch damage due to dry material burning on the orchard floor. Two of the monitoring sites were affected by a blow torch fire: Rosy Glow with four damage levels and Kanzi™ with two damage levels. Both varieties were grafted onto M9 and trained to a central leader, with Rosy Glow planted in 2008 and Kanzi™ in 2010. Each plot consisted of five trees in Rosy Glow and 10 trees in Kanzi™, with each damage level (slight, moderate, severe and extreme) replicated four times in both monitoring sites. The damage levels were determined by visual assessment of the canopy and the location of the plots from the fire front.

A third monitoring site was set up in autumn to assess the effects of slow cooker fire on the trunk and lower branches. This site was planted with Royal Gala grafted onto M26 in 1992 and trained to a central leader. Here, four damage levels were determined by autumn leaf colour (green, green/yellow, yellow, red), with plots consisting of five trees replicated four times. Due to the type of fire, the five trees were often not together in groups, but each replicate was within the same area in the orchard. Fire damage categorisation using leaf colour differences was based on earlier destructive assessments of phloem damage, which showed that limited NSC movement from the canopy to the roots could lead to red colouring of leaves in autumn.

In both blow torch sites, maturation and harvest parameters (e.g. apples per tree and apple size) were determined for several growing seasons after the fire. For the slow cooker site, these were assessed in the growing season following the fire and for three consecutive harvests in all three monitoring sites. The yield assessment consisted of counting apples from the middle three trees in a plot, weighing 20 apples and transporting them to the laboratory for further analysis. The fruit assessment included total soluble solids (TSS), juice pH and total acidity (TA), colour, firmness and starch scores. In addition to the fruit parameters, storage quality was monitored from two harvests, for each site, on 100 apples from each plot (see the section on apple quality and post-harvest assessment). Wood and root samples were taken from all sites at key developmental stages (i.e. dormancy, flowering, 70% fruit size, and harvest) during multiple growing seasons to determine NSC in reserve tissues. The allocation of carbohydrates and tree performance will provide information on the phloem function and source-sink relationships. In addition, tree nutrient status was monitored at the four development stages in the growing season by collecting 25 leaves from the middle of new shoots of trees in each plot. These leaves were washed, dried and analysed for nutrients. In addition, flower numbers were assessed from the lower and upper canopy on the middle tree of each plot, with canopy size determined in summer using a canopy analyser (LAI-2200C, LI-COR Inc, Nebraska, USA), when the leaf area was at the maximum size and reported as leaf area index (LAI).

Management trials in NSW

Management sites were established for both fire damage types in apples as for the monitoring sites. The Rosy Glow blow torch trial area consisted of two rows in the fire-damaged area of the orchard. About two-thirds of the trees were poled in summer by the orchard manager a few weeks after the fire. Trees used were either poled or not, and six treatments were set up in winter 2020. These included a control, poling in winter, and poling in summer, as indicated above. The summer poling was also the basis for three further treatments: cutting the leader in half; cutting the leader to trunk height; and the last treatment was weak trees, determined by the level of regrowth in winter from poling in summer. Other trees that were considered weak were not used for any of the five tree treatment plots. All treatments required some pruning and stringing down in winter to rebuild the tree structure and canopy. As in the Rosy Glow site, three treatments were implemented in winter 2020 for the Kanzi™ trial in the blow torch fire-affected and fire-free areas of the orchard. Treatments included a control, poling, and branch cutting to half the length. The plots consisted of 10 trees each (due to the smaller tree size), replicated four times. The slow cooker Royal Gala site consisted of six treatments, replicated four times, with five trees in each plot. Here, the treatments included a control, winter poling, removing half the branches, weak trees (judged by leaf colour in autumn) and two crop removal treatments (50% and 100%), implemented in winter 2020. Yield and yield parameters were collected over the following three growing seasons for Royal Gala and Kanzi™, while in the Rosy Glow trial, data collection was extended for another growing season due to the severity of one of the treatments (cutting leader back to trunk). The fruit parameters from the various treatments, were assessed at harvest. Root and wood samples were taken at four key phenological stages for NSC analysis with canopy size assessment at the same time.

Management trials in SA

Two South Australian orchards in Lenswood were included in SARDI's fire recovery investigations: a Rockit™ apple orchard (blow torch fire) and a multi-variety cherry orchard (slow cooker fire). Fire damage was assessed at both sites immediately post-fire in 2020, with trees categorised into five damage levels, ranging from zero damage to dead. At the apple orchard, damage categories formed distinct zones extending from the fire front. In contrast, the cherry orchard had a more random distribution of damage categories, with very few trees being classified as no or low damage. At the end of the 2020 growing season, three remedial pruning treatments were applied to three fire damage categories at both sites. Treatments included pruning to live wood (control), poling (removing all laterals and 25% of height), and complete canopy removal (heading cut above graft union). The apple orchard experiment used a split-plot design with five replicates of three pruning treatments within each fire damage zone. Due to the random distribution of damage and the lack of uniform buffer zones, the cherry orchard had single tree plots with 40 replicates of randomly allocated pruning treatments. Over five seasons, the interaction between fire damage level and pruning treatment was assessed using canopy growth, yield, and fruit quality at harvest measures. In 2021 and 2022, additional apple samples were sent to NSW DPIRD for storage quality assessments. The effect of fire damage on metabolite distribution was analysed through annual dormant sampling of root and trunk tissues. Geospatial mapping of orchard recovery and/or decline was informed by biennial tree mortality measures.

Apple quality and post-harvest assessment

Determining physiological maturity and fruit quality at harvest are critical because pre-harvest growing conditions directly affect fruit quality post-harvest, including storage life. This aspect of the project investigated the longer-term effects of fire damage on fruit maturity, ripening behaviour and storage in Rosy Glow and Kanzi™ fruit for successive growing seasons. Storage trials were also conducted on Gala and Rockit™ from the Adelaide Hills trial site. Fruit was stored and assessed in post-harvest laboratories at the Centre of Excellence for Market Access at the NSW DPIRD's Ourimbah site. Standard fruit maturity and quality measures included external appearance (e.g. background colour, scald, rots), internal disorders, fruit firmness, soluble solids content (SCC, %), titratable acidity and starch index. Where necessary, if it contributed to the interpretation of the storage outcomes, internal ethylene concentrations, ethylene production rates and respiration rates were also determined.

Controlled experiment

From autumn to early summer 2024, potted three-year-old Pink Lady trees were exposed to five heat loads. Pine needles were used to simulate a slow cooker fire. Before treatments started, three trees were destructively harvested to establish a physiological baseline for photosynthesis, transpiration, stomatal conductance and NSC. The fire treatments were replicated nine times to allow for three destructive harvests for each category of trees at 3, 6 and 8 months after the fire treatment: in mid-spring, around flowering and early summer. Photosynthesis and transpiration measurements were taken using a Li600 gas analyser (LI-COR Inc, Nebraska, USA) to capture short-term (1, 3 and 5 weeks) and long-term (33 weeks) effects of a slow cooker fire on trees. The trees were separated into branches, trunk and roots, then washed, dried and ground for NSC analysis using an enzymatic assay and colourimetric determination. Trunk images were taken from cut sections to visually assess the damage to the phloem and xylem by the different heat loads.

Grower engagement and resource provision

Demonstration sites in Bilpin provided wider geographical relevance at the beginning of the project. While the damage variability was minimal, we captured a few grower techniques to use as case studies and provide insight into recovery methods. The Rosy Glow site at Batlow was also used as a demonstration site as part of a workshop and a field walk. In addition, the apple blow torch site and cherry slow cooker site in Adelaide Hills were used as demonstration sites. The latter allowed some insight into the response and recovery of a tree crop other than apples. These case studies, combined with the scientific data generated from the project, have provided valuable insight into how growers make decisions and what motivates them. Additionally, the outcomes and updates of the project, with the various components, were presented at workshops and seminars or as part of Apple and Pear Australia Ltd (APAL) events at Batlow, Bilpin, Orange and Adelaide Hills. Further, three industry publications were produced, and a post-fire manual incorporating the findings of various components was completed towards the end of the project.

Literature review and publications

A literature review on the effects of bushfires on tree crops, with a focus on vegetative and reproductive development and fruit quality, was completed. The lack of research and consequent publications in this field expanded the scope of the review to include information on the effects of other abiotic stress factors (e.g. frost) that lead to trunk and phloem damage. Studies on the effect of fires on forest trees, which were more prevalent in the literature, were also reviewed. For example, the recommended non-destructive method for determining trunk damage in forest trees can be used for fruit trees. Several scientific papers were written and presented at three international ISHS symposia in France, Spain and the USA; these were from the research performed in the monitoring sites on the effect of fire on tree nutrition and smoke taint in cider. Further reviews relevant to the project on plant nutrition, climate change, and carbohydrate dynamics of perennial crops were presented at two of these meetings. International travel associated with these symposia also led to interactions with other scientists on fire damage/recovery of orchards and related topics, such as climate change and extreme weather. Further scientific publications have been drafted and are included as appendices.

Results and discussion

This project comprised several components that enhanced our understanding of the effects of bushfires on horticulture production systems, how to manage the trees after a bushfire and minimise the effect of such extreme events. The trials showed that apple trees damaged by blow torch fires (radiant fires) recovered by the second growing season after the fire, while recovery from a slow cooker fire varied depending on the extent of damage to the trunk and vascular system. This was clarified in an experiment with different damage levels. Remedial pruning showed that poling was the most suitable option for recovery when implemented a few weeks after the fire. Fruit quality parameters and storage life, particularly in the growing season when the fires occurred, were influenced by fire. Various presentations and publications, particularly the fire recovery manual, outlined tshe effects and severity of damage from the 2019–20 bushfires. This manual and the literature review describe how to manage the orchards after a fire and how to make these horticulture systems more resilient.

Monitoring trials in NSW

Damage to trees and orchard recovery varied with the different fire types as did the spatial variability. In the orchards that received blow torch fire, tree productivity was considerably compromised in the following growing season as they produced fewer flowers, and only a few apples were harvested from severely affected trees. However, the fruit assessments did not show differences between the various levels of damage, except for fruit ripeness and firmness. Similarly, there were only minor detectable effects on leaf nutrient status and NSC concentration in the wood or root tissues. It was somewhat expected that both would decline due to canopy loss by the fire; the nutrients in leaves would have been lost from the tree as they could not move back to the perennial structures in late autumn. Damaged canopy mostly recovered after the fire, but this would have used a considerable amount of NSC and assimilates would not have been produced for much of the remaining growing season. In the second growing season after the fire, the trees showed no differences in productivity and leaf area index (LAI) between the damage levels and, therefore, were well recovered. This suggests there might have been damage to flower buds and/or local deficiency of NSC/nutrients. The much lower crop load in the growing season after the fire could have also contributed to the recovery in the following growing season, allowing the trees' carbon balance to improve.

In a Royal Gala orchard that was damaged by a slow cooker fire, the damage to the trees varied, which was indicated by the differences in leaf colour in late autumn. The severely affected trees declined over the following growing seasons, and some trees died. They also had poorer canopies in the growing season after the bushfire, although the LAI did not differ from the other damage levels (slight, moderate, severe). Interestingly, these trees had substantially more fruit, which were smaller and had higher juice TSS and lower pH than the other damage levels. In the following season, yields from the severely affected trees were less than half of those from trees that were only slightly affected by the fire. The more damaged trees had lower NSC concentrations in the roots than trees that were only slightly damaged. This was most likely due to compromised phloem, reducing the amount of assimilates produced by the canopy from reaching the roots. These trees were also most deficient in macronutrients, confirming the compromised root function and growth due to the lack of NSC supply, limiting soil nutrient uptake. A further study on Bravo apple trees at Batlow emphasised the late decline and death of trees over several growing seasons after the bushfire, with a cumulative mortality of 31% of the trees by the third season. There was a 12% mortality immediately after the fires, 7% in the first season, 11% in the second season and 1% in the third season. Overall, the damage caused by a slow cooker fire is more difficult to assess non-destructively and causes more devastation that could impede productivity and quality over a longer time. An orchard affected by this type of fire will require careful damage assessment to estimate the percentage of trees severely affected and what action should be taken to mitigate the long-term effects of fire.

Management trials in NSW

Management trials in NSW allowed different options for enhancing fruit tree recovery from bushfire damage to be explored. The objective was to minimise the damage variability in the orchard caused by fire and the timeframe for achieving uniformity.

For the blow torch Kanzi™ site, LAI values were not different ($P>0.05$) in the first and second seasons after the bushfire. However, by the third season when full canopy recovery had been reached, poled fire-affected trees had the highest LAI at harvest (apart from the control). Canopy recovery in the blow torch Rosy Glow site was achieved by the second season for most treatments. However, LAI values, which were not significantly different between treatments, showed a longer recovery (three seasons) when all branches were removed in the winter after the bushfire, and when the tree leader was cut to the trunk and all branches were removed. For the slow cooker Royal Gala site, canopy recovery was achieved in all treatments by the second season after the bushfire.

Yield in the blow torch Kanzi™ trial was reduced ($P<0.05$) at the first season assessment by the remedial pruning treatments, with control trees having the highest yield. By the third season, fire-affected trees still had significantly lower ($P<0.05$) yield than the fire-free trees.

For the blow torch Rosy Glow trial, the severity of the remedial treatments also reduced yield ($P<0.05$) during the first two seasons (seasons 2 and 3). The yield assessment in season 4 showed less variability as only control trees had significantly higher yield values ($P<0.05$).

As with the other two trials, remedial pruning significantly reduced ($P<0.05$) yields in the first season after bushfires in the slow cooker Royal Gala trial. By the second season, tree recovery resulted in a more uniform yield, which was not significantly different ($P>0.05$). This continued to the third season of assessment when the poling and half-branch removal treatments recorded the highest yield values.

In all three trials, apple quality parameters were not different in the first, second and third seasons after the bushfires for all remedial treatments ($P>0.05$). However, in the blow touch sites, fruit from the poling treatment had higher starch content and total soluble solids (TSS) than fruit from other remedial treatments by the last season of fruit quality assessment.

Overall, poling was the best option for canopy size and yield at all sites, particularly if conducted a few weeks after the fire rather than in the following winter. Other remedial treatments had noticeable drawbacks. For example, it took an extra growing season for blow torch Rosy Glow trees to recover because of the more severe remedial treatments that were implemented. The most severe treatment (cut back to the lower trunk) took four growing seasons to return to similar production levels as the untreated trees. Poling also has the advantage of being easily explained to pruners and better potential for reducing the variability in the rows due to fire. These benefits will simplify the long-term management of orchards.

Management trials in SA

SARDI's maps revealed contrasting recovery responses in tree health and mortality in orchards exposed to short term radiant heat (blow torch fire) versus prolonged contact with fire (slow cooker fire).

At the Rockit™ apple site, affected by radiant heat, recovery was predictable. Only the rows closest to the fire front needed replacing. Damage severity decreased with increasing distance from the fire, and the most damaged surviving trees returned to commercial production rates after remedial pruning. While 20% of the orchard was killed by the fire, only an additional 5% (mainly in the extreme damage category) died over the next five years. Notably, 74% of trees in the extremely damaged zone survived to commercial production, with no deaths in the low to high damage categories.

Conversely, recovery was unpredictable at the cherry site, most likely due to reduced vascular connection from prolonged heat around the trunk. Recovery was sporadic and return shoot growth was weak. Fourteen per cent of the orchard died during the fire, and an additional 17% of trees died over the following five years. After this, 25% of the surviving trees continued to display poor growth and signs of declining health, suggesting further tree deaths could be expected.

Three remedial pruning treatments for different fire damage categories were assessed at both orchards. Canopy response to remedial pruning was most favourable at the apple site, where trees returned to full-size productive units (LAI >1.8) within three to five seasons. Conversely, tree vigour in the cherry orchard declined (LAI <1.0) throughout the five-season investigation. Only those with low to moderate fire damage had return growth. The cherry trees in the high to extreme fire damage categories had reduced vigour, regardless of remedial pruning treatment.

While the response to remedial pruning was most favourable at the apple site, productivity interactions between the extent of fire damage and the type of remedial pruning treatment followed similar patterns at both orchards. The pruning control (pruning trees back to live wood) gave the most favourable yield response in the lower damage categories at both sites with cumulative five-year tonnages being at least 27% higher than other pruning treatments. However, this pruning strategy was time-consuming and needed to be applied during the growing season when the presence/absence of live growth could guide pruning decisions.

Poling trees by removing the laterals and the top quarter of the canopy height was easy to instruct, quick to apply, and did not require the presence of actively growing leaves to guide pruning decisions. In the worst fire-affected trees, the poling treatment gave an equivalent yield response to the more time-consuming control pruning. Complete canopy removal (via a heading cut) was not a viable remedy at either site, with crop loads being uneconomically small and of poor quality.

Apple quality and post-harvest assessment

Fruit quality and storage are crucial to consistently delivering high-quality fruit to the consumer throughout the year. Storage trials on fruit from fire-affected orchards were conducted on various apple cultivars (e.g. Kanzi™, Gala, Rocket, and Rosy Glow) over successive years. In Batlow, the fires occurred nine weeks before harvest and some marketable fruit was produced from severely affected trees. While these trees had some physical damage (such as leaf loss), the fruit had no physical symptoms of direct damage. However, this fruit was smaller and firmer, with lower starch reserves, low fruit acidity and much lower sugar levels as the fruit ripened. This shows that fire-affected fruit had lower carbohydrate reserves and this reduced its long-term storage. In general, fire-affected fruit had lower total soluble solids (TSS) than fruit from unaffected trees at harvest and during storage for two seasons after the bushfire. This demonstrated the ongoing effects of fire on damaged fruit trees and the fruit they produce. Similarly, the levels of starch reserves in the fire-affected Kanzi™ apples were lower than in the fire-free fruit at harvest and during storage. Furthermore, the TSS levels in the fire-damaged fruit were lower than in the undamaged fruit.

Depending on the timing and severity of the bushfire, it is possible to salvage marketable fruit from the orchard following a fire. However, this fruit should be processed and sold as quickly as possible and not put into long-term storage. Poor carbohydrate allocation during fruit growth and maturation reduces fruit quality and storage life. It is difficult to predict the quality and storage life of fire-affected fruit, but our experience shows that any fire damage can affect fruit quality, and this fruit should not be put into long-term storage.

Controlled experiment

A controlled burning experiment with varying heat loads was performed to enhance our understanding of how slow cooker fires damage tree trunks and the lower canopy. Cross-sectional observation of smouldered tree trunks confirmed the girdling effect seen in the field, with severity increasing with the heat load of the combustible materials below the trees. The level of fire dose (burned amount of combustible material around the trunk) also determined the degree of decline in root biomass and total NSC. Fire significantly decreased ($P<0.05$) photosynthesis almost immediately in the weeks after the fire in autumn (middle of April) until leaf-fall in the two highest fire doses. These differences in assimilation were not different ($P>0.05$) between the control and the highest fire dose treatment in the early summer of the following growing season. Furthermore, the two highest doses of fire resulted in the lowest leaf transpiration and stomatal conductance throughout the experiment. These observations confirmed earlier findings from the field, showing that fire dose negatively effects the vascular system and roots of trees. It also provided additional information about the effect of fires on short-term (up to six weeks after) tree assimilation and transpiration, which could have contributed to the slower recovery rate in extremely smouldered trees.

Grower engagement and resource provision

The interaction with the industry in Batlow started in summer 2021 with a field day that included several presentations before the visit to the Rosy Glow monitoring and experimental site. An orchard walk was also conducted in Lenswood (Adelaide Hills, SA) that summer, following on from a workshop in the previous winter. An article was published in the *Australian Fruitgrower* (APAL magazine) in spring 2021 on fire-proofing orchards and post-fire management strategies.

In the 2021–22 growing season, two orchard walks were held in Bilpin (NSW) and Lenswood (Adelaide Hills) as well as a presentation at Batlow (AusCider 2022) on smoke taint in cider. Presentations were also given on the project in an online workshop to the bushfire technical advisory committee in Queensland for a project titled 'Bushfire preparedness, recovery and resilience in horticulture', undertaken by Growcom. Two further orchard walks were conducted in the following growing season in Batlow and Lenswood as part of the APAL Future Orchard program. In winter, two orchard walks were held in Bilpin with the Bilpin/Sydney growers meeting and another one in Lenswood as part of the PIPS 4 Profit Program.

In the 2023–24 growing season, a presentation was given to local fruit growers in Lenswood in spring. In autumn, at a workshop in Orange (NSW), several presentations were given on recovering horticulture from bushfires in conjunction with talks relating to the PIPS 4 Profit Program funded by Hort Innovation.

In the 2024–25 growing season, two further presentations were given in Lenswood to growers and food producers. The engagement concluded towards the end of 2024 with the production of the bushfire manual titled '*Bushfires in orchards: a guide to preparedness, response and recovery*'. The feedback from the growers emphasized the importance and relevance of the work, particularly for orchards that are surrounded or near vegetation. A key message was also that the findings and resources of the project should continue to be communicated to growers in the future through various grower forums.

Literature review and publications

A literature review titled '*Building bushfire resilience in horticultural production systems: important insights from Australia*' was published in 2023 (Idowu et al. 2023a). The review provided comprehensive coverage of the various effects of bushfire on horticultural production systems including direct and indirect effects on tree physiology. It also provided detailed commentary on the effects of bushfires on carbohydrate dynamics in fruit trees and provided insights into the physiological disruptions caused by fire. In addition, the review recommended practical strategies for building resilience, such as using green strips and prescribed burning, which are substantiated in both traditional knowledge and contemporary research.

Four papers were published or are currently in press as part of the three international ISHS symposia presentations attended by project team representatives. These are the International Symposium on Plant Nutrition, Fertilization, Soil Management of the XXXI International Horticultural Congress in Angers (France 2022); the III International Symposium on Beverage Crops in Murcia (Spain 2023); and the X International Symposium on Plant Nutrition of Fruit Crops in Wenatchee (USA 2024). The three key papers are '*Nutrient status, canopy size, crop load and fruit quality of a fire-affected Royal Gala orchard: implications for orchard management*' (Idowu et al. 2023b); '*The effect of bushfires on apple and cider smoke taint precursors and sensory characteristics*' (Dodds et al. 2024); and '*Nutrient status of apple trees affected by bushfires: does nature of fire affect tree nutrition?*' (Idowu et al. 2025a). Three other project-related publications form part of the output of a collaborative study with Charles Sturt University. Two other publications on the recently completed controlled experiment and management trials are in draft form, with completion expected this year.

Outputs

Table 1. Output summary

Output	Description	Detail
Post-fire recovery articles in industry magazines to support the 'post-fire best practice' manual.	Minimum of two industry-orientated articles in growers' journal	Article published in *Australian Fruitgrower* Spring 2021 Article published in *Australian Fruitgrower* Autumn 2023 Article published in the *Australian Nutgrower Magazine* Winter 2023
Academic peer-reviewed papers in international horticultural journals.	Minimum of two peer-reviewed journal articles in international journals.	Article published in *Frontiers in Sustainable Food Systems* (2023) Article published in *Trees* (2024) on the related joint study with Charles Sturt University One article published in *Acta Horticulturae* in 2023, two articles published in 2024 and two articles are in press to be published in 2025 Article to be submitted in 2025 (see appendix)
Conference presentations	Relates to the scientific articles above	One presentation at the International Horticultural Congress (IHC) in Anger, France (August 2022) Two presentations at the International Symposium of the International Society of Horticulture Science (ISHS) in Murcia, Spain (April 2023) Two presentations at the International Symposium of the ISHS in Wenatchee, USA (June 2024)
Organise, develop and deliver post-fire recovery workshops.	Three workshops and other extension activities, including orchard walks and field days.	Apple and Pear Growers Association of South Australia (APGASSA) and Cherries Growers Association of South Australia (CGASA) Workshop – Adelaide Hills (July 2020) Field day and presentations – Batlow (February 2021) Orchard walk – Adelaide Hills (March 2021) Presentations within online workshop to bushfire technical advisory committee – Queensland (September 2021) Orchard walk – Adelaide Hills (March 2022) Presentation at AusCider – Batlow (May 2022) Orchard walk and presentations – Bilpin (June 2022) Orchard walk – Batlow, in conjunction with APAL Future Orchard (February 2023) Orchard walk – Adelaide Hills, in conjunction with APAL Future Orchard (February 2023) Orchard walk and presentation – Bilpin (June 2023) Orchard walk – Adelaide Hills in conjunction with PIPs 4 Profit Program (May 2023) Bushfire one-page advice notice for growers, Stanthorpe, Queensland (November 2023) Presentation to local fruit growers – Adelaide Hills (November 2023) Workshop and presentation – Orange (NSW) in conjunction with PIPs 4 Profit Program (May 2024) Grower's workshop – Adelaide Hills (May 2024) Presentation at the Big Map workshop, Snowy Valley Resilience Hub, in conjunction with NSW Reconstruction Authority and Disaster Relief – Batlow (July 2024)

		Presentation to growers – Adelaide Hills in conjunction with PIPs 4 Profit Program (July 2024) Presentation to SARDI's crop science group (October 2024) Presentation online to Apple and Pear Strategic Industry Advisory Panel (November 2025)
Development of the 'post-fire best practice' manual.	Preparation of hard and electronic versions of the 'post-fire best practice' manual.	The manual titled '*Bushfires in orchards: a guide to preparedness, response and recovery*' was uploaded to the NSW DPIRD website in November 2024 (revised edition in May 2025) and the printed version is scheduled for May 2025.
Activities	**Description**	**Detail**
Monitoring and experimental sites	Data/sample collection Sample/data analysis	Three monitoring sites with different damage levels were assessed (Batlow), and tree mortality was monitored at another site. Five experimental sites with different management recovery treatments (Batlow and Adelaide Hills).
Post-harvest/storage trials		Apples were collected from different monitoring sites/damage levels and storage parameters were determined.
Controlled experiment		An experiment was conducted on apple trees exposed to different fuel loads.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Improved understanding of the effect of bushfires on the horticulture production systems	Sustainability of economic returns from horticulture production following bushfires	The short and long-term effects of bushfires were investigated in three monitoring sites.	Milestone Reports and publications/appendices
Practical and scientific knowledge of tree recovery management practices		Five management sites were established to determine tree recovery options from slow cooker and blow torch fires and one controlled experiment for a comprehensive study of the effects of smouldering fire on tree physiology.	Milestone Reports and publications/appendices
Strategies to minimise the effects of fires in orchards	Bushfire effects on orchards mitigated/minimised	The strategies have been initially identified in a scientific literature review and then further outlined in the post-fire management manual.	Scientific review paper and the best practice post-fire management manual
Information to optimise orchard management recovery after fires available		Five management sites were established to determine recovery options for trees damaged by slow cooker and blow torch fires.	Milestone Reports and publications/appendices
Improved post-fire orchard management and preparedness through extension activities		Publications in industry-oriented journals, workshops, field days/orchard walks	Milestone reports and appendices
Best practice post-fire management manual developed (digital and printable)		The manual was produced towards the end of the project in late 2024 and outlines practical steps for building resilience in orchards and short- and long-term responses to orchards damaged by fire.	'Bushfires in orchards: a guide to preparedness, response and recovery' on the NSW DPIRD website and printed.

Improved understanding of the effects of bushfires on horticulture production systems

By monitoring recovery metrics at three sites in Batlow, the short and longer-term effects of smouldering and radiant fires on apple tree functionality and productivity were investigated. At the Rosy Glow and Kanzi™ blow torch sites, poor apple quality at harvest extended to the second season. Productivity was reduced to a few apples per tree in the growing season after the fire due to the effect of radiant fire on fruit set. By the second growing season, production levels in both orchards had recovered.

The slow cooker fire that damaged the tree bark and vascular system also affected the tree's lower canopy. The severity of damage influenced tree performance in subsequent growing seasons, ultimately resulting in the death of some of the trees. This was depicted in a Bravo apple orchard, which served as an additional observation site. The mortality was 12% immediately after the fires, further losses occurred with 7% in the first growing season, 11% in the second and 1% in the third.

Trees affected by blow torch fire recovered well by the second growing season after bushfires, while the slow cooker damage was more difficult to assess, with the effect extending to several growing seasons after the fire. Assessing root and wood carbohydrates, as well as leaf nutrient status, indicated the dysfunction of the vascular system in severely damaged trees.

Practical and scientific knowledge of tree recovery management practices

Five management sites were established in Batlow (NSW) and Adelaide Hills (SA) to determine recovery options from both slow cooker and blow torch fires. Several treatments were implemented with three trials designed to incorporate the different damage levels (slight, moderate, severe, and extreme). At the blow torch sites, all remedial pruning treatments were effective in bringing the trees back to optimum production levels, but the time to recover was two to four growing seasons with the more severe pruning treatments. Canopy measurements, productivity assessments and tree carbohydrate level monitoring in perennial organs supported the observed tree recovery.

How the Royal Gala trees in Batlow were managed after the slow cooker fire did not influence their recovery. This is probably due to less significant fire damage to the vascular system and limited interruption of assimilates in severely damaged trees. The lower root carbohydrate reserves corroborated this conclusion. In contrast, recovery was limited in more damaged trees in the cherry orchard at Adelaide Hills, where the treatments were implemented at different damage levels. Overall, poling worked well on most occasions returning to pre-fire production levels after two growing seasons and would be best undertaken within a few weeks after a fire. Poling is also easy to implement and enhances uniform tree structure.

Strategies to minimise the effects of fires in orchards

The prediction of increased frequency and intensity of bushfires in Australian horticulture regions means that proactive measures need to be explored to protect these production systems. Strategies must be holistic and consider the native vegetation or forest plantations, which are often contiguous to orchards. Managing the vegetation within the orchard should be an annual preparatory activity before bushfire season begins. This will add an additional layer of protection for minimising potential damage from the more devastating slow cooker fires. More importantly, orchards must be designed to minimise the effect of bushfires and other extremes (e.g. heat waves or frost). Proper design starts with appropriate site selection, infrastructure, trellis, and irrigation systems. The proximity of the orchard to other vegetation and the choice of trees around the orchard also need thoughtful consideration. Such strategies have been described in the literature review and further outlined in the post-fire management manual.

Information to optimise orchard management recovery after fires available

Five trials were undertaken in Batlow and Adelaide Hills to investigate several orchard management options to help trees recover from bushfire damage. The required remediation and success of tree recovery depended on the fire type and amount of damage to the tree. Orchards compromised by slow cooker fires need to be carefully assessed so that badly affected trees are promptly identified and replaced. This becomes difficult because non-destructively determining the extent of damage to the vascular tissue is challenging until appropriate methods are discovered. Badly smouldered trees tend to die in the growing season(s) after a bushfire. Depending on the tree's reproductive stage during the bushfire, crop removal after the fire or in the following growing season could reduce the stress on damaged trees, provided a sufficient part of the bark (phloem) is still functioning.

Orchards compromised by blow torch fires need remedial pruning to be adjusted to the level of damage; for slight damage, no action might be required, while for severely damaged trees, the leader might need to be cut back to the trunk. Tree replacement could be a more logical option if the level of damage is very high.

Poling the trees in the same season of the fire was an easier option, improving the regrowth and vitality of the trees sooner than conducting this form of pruning during dormancy. This pruning option could be the best way of reducing fire-caused orchard variability.

Improved post-fire orchard management and preparedness through extension activities

Workshops and field days/orchard walks have been held, publications in industry-oriented journals have been published and a post-fire management manual has been completed. The extension activities were held in Batlow and Bilpin (NSW) and Adelaide Hills (SA). Additionally, two online workshop presentations were delivered to the bushfire technical advisory committee (Growcom, Queensland) and a comprehensive workshop in Orange towards the end of the project. Extension activities in various locations attracted mostly local growers and producers and were often in conjunction with the APAL Future Orchard program. This maximised the participant numbers and many growers were exposed to this novel work. Today, there is a better understanding of the effects of fire on horticulture production, the best recovery options and strategies for building more resilient orchards.

Best practice post-fire manual on effective assessment and management developed

The manual titled '*Bushfires in orchards: a guide to preparedness, response and recovery*' was published on the NSW DPIRD website in November 2024 (revised edition in May 2025). The printed version is in production and will be distributed at relevant extension activities. The manual focuses on bushfire damage to orchard trees and infrastructure and recovery options for the two types of fire. It also describes the annual preparations required in orchards before the start of the bushfire season and longer-term orchard improvements towards more resilient production systems. Lastly, the manual includes several case studies from producers who were affected by the bushfires in the 2019–20 growing season and who shared their experiences and what they could have done differently.

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
Effectiveness		
1. To what extent has the project achieved its expected outcomes?	The project has largely achieved its expected outcomes: Recovery metrics from monitoring sites in fire-affected orchards and controlled experiments have greatly enhanced our understanding of the effects of bushfires on fruit tree functionality, yield and post-harvest fruit quality. The pruning treatments indicated that complete tree branch removal (poling) is most effective for the two fire types observed in the orchards. Poling was highly effective in the vegetative and reproductive recovery of fire-effected apple and cherry trees. The project provided an in-depth understanding of the devastating nature of smouldering fires to fruit trees. Due to the destruction of the vascular tissues and the negative effects on tree physiological attributes, the long-term effects of smouldering bushfires were identified. One of the project outputs is a manual detailing various strategies for responding to fire damage in orchards and how to minimise the effects of fires. The manual provides comprehensive guidance on proactive bushfire management strategies for building resilience in orchards.	While the project has largely achieved its expected outcomes, there is an important aspect of the smouldering fire damage assessment that needs to be improved. Prompt assessment of vascular tissue damage in orchard trees exposed to a smouldering fire will assist growers in deciding whether to remove or retain the trees, reduce losses and enhance recovery. The method currently in use for this assessment is crude and destructive. Future improvements should aim at developing non-destructive, easy-to-use equipment for prompt assessment of fire-caused vascular tissue damage. The current project focused on developing management strategies to respond to bushfire damage to orchard trees. Future opportunities should explore ways to be proactive by building bushfire resilience in horticultural production systems. Considering the role of orchard floor vegetation in smouldering fires, future improvements and developments must be holistic to consider both the carbon sequestration and flammability potential of dominant cover crops in Australian orchards. This is necessary to avoid consequential carbon losses and orchard damage from bushfires if the emphasis is only on the carbon sequestration ability of cover crops.
Relevance		
	To what extent has the project met the needs of industry levy payers? The project has proven to be highly relevant to the needs of the industry levy payers as shown by the positive feedback at the various extension activities. After the 2019–20 bushfires, growers were unsure how to respond to bushfire tree damage. There were no documented management strategies to guide them. With the completion of this project, growers now have a better understanding of how bushfires	The project outcome documents, particularly the manual, should regularly be reviewed and updated as new knowledge about bushfire resilience in horticultural production systems emerges. Efforts should be directed at developing new projects to explore novel ways of protecting orchards from bushfires and other abiotic stressors.

	affect tree functionality in the short and long term and what possible strategies could be deployed to mitigate the effects. Through this project, strategies for building resilience for Australian orchards from future bushfires have been well documented. Developing useful strategies is important because climate change will increase the frequency and intensity of bushfires.	
Process appropriateness		
3. How well have intended beneficiaries been engaged in the project?	To what extent were levy payers and other industry players engaged? Have regular and useful updates about the project been provided? The project adopted an ongoing engagement method to ensure levy payers were updated throughout the project. Engagement activities included seminars, workshops, and regular orchard walks to show participants important project outcomes, regular updates from the Project Reference Group (PRG) members, publication of industry articles and production of a post-fire management manual (online and printed versions). The feedback from growers emphasized the importance of maintaining the awareness of the resources produced beyond the project.	While regular and useful updates were carried out during this project, the interest of stakeholders in the subject matter dwindled at some point, largely because bushfires were no longer at the forefront compared to other competing concerns a couple of seasons after the bushfires. In this era of climate change, growers and other stakeholders must always be prepared. Other information sources such as newsletters, e-mails and blog articles must be strategically and systematically deployed to achieve the objective of constant awareness, preparedness and knowledge improvement.
4. To what extent were engagement processes appropriate to the target audience/s of the project?	Did the project engage with industry levy payers through their preferred learning style? How accessible were extension events to industry levy payers? The engagement processes were strategically designed for growers and other stakeholders to ensure that project findings were conveyed regularly and in a way that would facilitate adoption. Extension events in NSW and SA (the main bushfire-affected regions) was mostly orchard walks where participants were taken through the monitoring and trial sites and discussions on observed outcomes were elicited. Before the orchard walks, growers, industry experts, representatives of the funding bodies, researchers and other stakeholders would often converge for prior discussions to serve as the basis for the orchard walk. Outcomes of trials were also published in growers' magazines and manuals for easy consultation by all stakeholders.	The engagement processes were appropriate but could be improved to sustain ongoing interest in project activities and outcomes. Other information sources such as newsletters, e-mails and blog articles could be strategically and systematically deployed to achieve this objective.
Efficiency		
5. What efforts did the project make to improve efficiency?	Is the project making efforts to improve efficiency? What are the lessons learnt that could improve future research delivery? A major lesson learnt on this project is to always anticipate risks to project delivery and develop ways to mitigate them. The risks associated with this project include the COVID-19 restrictions, unanticipated removal of trees at monitoring and trial sites, low grower engagement during some extension activities, biosecurity emergencies and their effect on staff availability, and loss of project staff, among others. These risks were adequately managed through the proactiveness, creativity and ingenuity of project team members such that the consequences of the risks were largely insignificant.	Risks must always be anticipated and managed on an ongoing basis.

Recommendations

This project enabled us to gain comprehensive knowledge about the damage to orchard trees and fruit from blow torch and slow cooker fires. This includes better understanding of fire damage assessments and the consequences for recovering or removing orchard trees. In addition, we developed some recommended actions required within the first weeks and months after a fire and for building fire-resilient orchards.

Assessing affected trees is the first step and should be done as soon after the fire as possible to decide what action should be taken for the trees and for harvest. The next step is fixing the infrastructure, particularly the irrigation system, which is important to minimise further damage to the trees. The visual symptoms for tree recovery are more reliable after a blow torch fire than a slow cooker fire. With the slow cooker fire, visual observations suggested the fruit would be too damaged to make a harvest worthwhile, and this was still evident in severely damaged trees in the following growing seasons. The blow torch fire accelerated apple maturation in the more damaged trees, and the effect on fruit size, firmness and acidity must be considered at harvest. In these trees, production recovered in the second growing season after the fires without any further input requirements and they should remain in the orchard.

In contrast, trees severely damaged by slow cooker fires had poor recovery, and tree removal would be recommended. This is particularly likely with young trees with a small trunk diameter. Since the non-destructive assessment is challenging for this fire type, unpredicted further losses can occur over several growing seasons, which can lead to an orchard that would be unviable. Therefore, further work is needed to assess conductive tissue damage on tree survival and performance, including finding non-destructive methods such as electrical resistivity tomography. This would result in a better-informed decision to maintain the orchard or remove/replace parts or all of the orchard following a slow cooker fire.

Any pruning required, such as removing all branches, should be done soon after the fire, as the remaining growing season's development can lead to faster recovery. Early pruning can also help with assessing new growth in winter to determine how badly the trees were affected and assist with the decision process. The remedial pruning level needs to be adjusted to the damage level and fire type; if the trunk is too severely damaged due to slow cooker fires, pruning or crop removal will not contribute to the recovery. For blow torch damage, the severity will determine the pruning, from cutting the trees back to the trunk to semi-poling or shortening branches to half the length. This later treatment, either conducted in the same season of the fire or in winter, results in the fastest recovery of the trees. The next level of remedial pruning is poling, which can also be done in the same season of the fire or in winter, requires more input for training and time to come to full production again. However, this approach is easier to implement and might help to reduce variability within the orchard. The next level of remedial pruning is cutting about 30–40% of the leaders off after poling. This might be required if the upper parts of the trees are more damaged and it could take three growing seasons to return to good production levels. However, if the upper part of the tree is severely damaged, cutting back the trunk below the lower branches is an option, but it could take four growing seasons to retrain and have good harvests. Replacing trees with these damage levels might be better several weeks after the fire.

Before the bushfire season, prepare orchards for potential fires. Backup power generators and firefighting resources should be assessed and upgraded if required, and more secure places for machinery and harvest bins should be determined to minimise losses. In addition, adjustments to the irrigation system might be required, such as adding overhead sprinklers and increasing the height of drip lines. Reducing the amount of combustible material under the trees will further minimise potential damage to drip lines and tree trunks. The fuel load in the bordering vegetation near the orchard should be reduced.

Future orchard design needs to incorporate the threat of bushfires, including site selection (landscape and water resources) and more fire-resistant infrastructure, such as sheds, trellis and irrigation systems. Also leaving suitable fuel break zones and/or planting more fire-resistant tree lines around the orchard. These adaptation strategies become crucial for established and developing orchards as dangerous fire days are predicted to increase.

Designing and developing fire-resilient orchards by using more fire-resistant vegetation around the orchard and under the trees would be a good approach. More information is required about reducing the effects of bushfires on tree physiology and reproduction. For instance, further understanding of bud and canopy damage due to blow torch fire damage requires further investigation. Similarly, more comprehensive studies should be undertaken on the effect on the vascular system and roots, as these get compromised by slow cooker fires. This would include developing a non-destructive way to assess damage in the field (e.g. electrical resistivity tomography). Such work will contribute to refining recovery options and decisions after bushfires. It is also advisable to undertake extension activities and workshops, particularly before the bushfire season in various horticultural production regions, by building on project findings and the post-fire management manual. The scope of the project has not allowed the outcomes to be fully conveyed to the growers, therefore there is a need for a follow up extension program, awareness creation and continuous use of available resources. This was also a key message from growers that relevant orchard management strategies and preparedness for bushfire events is crucial in view of climate change as it is predicted that there will be an increase in dangerous fire weather days in the future.

Refereed scientific publications

Journal articles

1. Dodds K, Wilkinson K, Holzapfel BP (2024) The impact of bushfires on apple and cider smoke taint precursors and sensory characteristics. *Acta Hortic*. 1387, 57–66. DOI: 10.17660/ActaHortic.2024.1387.8 (linked to project)
2. Holzapfel BP, Smith SP, Rossouw G, Field SK (2024) The function of source-sink relationships in grapevines on grape and wine production. *Acta Hortic.* 1387, 11–24. DOI: 10.17660/ActaHortic.2024.1387.2 (linked to project)
3. Holzapfel BP, Wegher M, Idowu OD (2025) The impact of climate change on nutrition of deciduous perennial cropping systems. *Acta Hortic*. (in press). (linked to project)
4. Idowu OD, Prakash R, Holzapfel BP (2025) The impact of different levels of smouldering fire exposure on Pink Lady apple tree physiology under controlled conditions. (draft in appendix)
5. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2023a) Building bushfire resilience in horticultural production systems: important insights from Australia. *Front. Sustain. Food Syst.* 7: 1173331. doi: 10.3389/fsufs.2023.1173331
6. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2023b) Nutrient status, canopy size, crop load and fruit quality of a fire impacted Royal Gala orchard: implications for orchard management. *Acta Hortic*. 1375, 153–160. DOI: 10.17660/ActaHortic.2023.1375.20
7. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2025a) Nutrient status of apple trees impacted by bushfires: Does nature of fire affect tree nutrition? *Acta Hortic*. (in press)
8. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2025b) How smouldering and radiant fires affect apple tree performance – the Australian experience (draft in appendix)
9. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2025c) Management of apple trees for optimum recovery from bushfires in three NSW apple orchards. (draft in appendix)
10. Rossouw GC, Idowu O, Gregson A, Holzapfel BP (2024) Simulated fire injury: effects of trunk girdling and partial defoliation on the reproductive development of apple trees (*Malus domestica*). *Trees,* 38 (5), 1323–1342. DOI: 10.1007/s00468-024-02555-0 (linked to project)

Whole books

11. Dodds K (2020) *Bushfires in apple orchards: observations from the 2019–20 season*. Tumut, NSW: Department of Primary Industries, 33 pages, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/1285392/Bushfires-in-apple-orchards.pdf (preceding the project)
12. Dodds K, Pitt T (2024) *Bushfires in orchards: a guide to preparedness, response and recovery*. NSW Department of Primary Industries and Regional Development, https://www.dpi.nsw.gov.au/agriculture/horticulture/pomes

Industry publications

13. Gregson A, Dodds K, Lewis J, Idowu O (2023) Bushfire recovery in hazelnuts: case study. *The Australian Nutgrower Magazine*, 38 (2), 23–27 (linked to project)
14. Idowu OD, Pitt T, Dodds K, Golding J, Fearnley J, Petrie P, Holzapfel BP (2021) Orchard fire-proofing and post-fire management strategies: A case study of the 2019–2020 bushfires. *Australian Fruitgrower*, Spring 2021, 15 (3), 63–65.
15. Rossouw GC, Idowu O, Gregson A, Holzapfel BP (2023) How bushfires affect apple productivity: preliminary cues from simulated injury. *Australian Fruitgrower*, Autumn 2023, 17 (1), 38–40. (linked to project)

References

Bär A, Michaletz ST, Mayr S (2019) Fire effects on tree physiology. *New Phytologist*, 223(4), 1728–1741. doi:10.1111/nph.15871

Bender GS (2012) Recovery from fire damage in avocado groves. Retrieved from University of California, http://cesandiego.ucanr.edu/files/272041.pdf

Collins C, Gao H, Wilkinson KL (2014) An observational study into the recovery of grapevines (*Vitis vinifera* L.) following a bushfire. *American Journal of Enology and Viticulture*, 65(3), 285–292. doi:10.5344/ajev.2014.13127

Dodds K (2020) Bushfires in apple orchards: observations from the 2019–20 season. Tumut, NSW: Department of Primary Industries, 33 pages, https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/1285392/Bushfires-in-apple-orchards.pdf

Grills A (2009) Recovery from fire damage in fruit orchards. Note Number: AG1376. Retrieved from https://agriculture.vic.gov.au/crops-and-horticulture/fruit-and-nuts/orchard-management/recovery-from-fire-damage-in-fruit-orchards

Krstic MP, Johnson DL, Herderich MJ (2015) Review of smoke taint in wine. *Australian Journal of Grape and Wine Research*, 21: 537–s553. https://doi.org/10.1111/ajgw.12183

Intellectual property

No project IP or commercialisation to report.

Acknowledgements

The authors would like to thank the Batlow apple orchardists who allowed us to use their orchards for this project, including Greg and Kristen Mouat, the Duffy family and Batlow Fruit Company Limited. We are also grateful for the support and assistance from Dr Thuy Pham, Maddy Kavanagh, James Freriechs, Steven Harden, Mark Bullot, Dr Baogang Wang (Beijing Academy of Agriculture and Forestry Sciences, China), Emma LeGal, Thiffen Allart, Dr Kein Nguyen, Di Hubbard, Orlando Holzapfel, Cabon Gladys, Bianca Bittau, Albane Meunier and Camille Chopineaux during various stages of this project.

Appendices

Appendices 1 to 10: publications (see section on refereed scientific publications)

Appendices 11 to 12: books (see section on whole books)

Appendices 13 to 15: industry publications (see section on industry publications)

Appendices 16 to 17: reports

16. Golding J (2025) Effects of fire on fruit quality and storage.
17. Pitt T, Idowu O, Shanmugam K, Graetz D, Petrie P, Dodds K, Fearnley-Pattison J and Holzapfel B (2025) Using pruning to manage the impact of bushfire damage to apple and cherry.

Appendix 18: cover photo

18. Holzapfel B (2020) Fire affected apple trees in autumn 2020, Rosy Glow trial site Batlow (taken 22/05/2020).