Manipulation of Whole-vine Carbon Allocation Using Girdling, Pruning, and Fruit Thinning Affects Fruit Numbers and Quality in Kiwifruit

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Abstract. We compared the long-term effects of whole-vine source-sink manipulation on yield, composition, and quality of fruit from mature field-grown kiwifruit (Actinidia chinensis Planch. var. chinensis ‘Hort16A’) vines. Four contrasting source/sink-modifying treatments were applied to vines each year from Spring 2003 to 2007: 1) control—standard canopy management techniques, no trunk girdle; 2) extended trunk girdle (ETG)—girdle was opened in late summer, kept open over winter, and allowed to heal the next spring; 3) “feast”—cropload was kept low and leaf numbers kept high, no trunk girdle; and 4) “famine”—fruit numbers were kept high and vines were heavily pruned to stimulate regrowth, no trunk girdle. Fruit from the famine vines were smaller with lower dry matter concentration (DMC; dry weight as a percentage of fresh weight) and had delayed maturity relative to fruit from the control vines. Return bloom was reduced in the famine vines, resulting in ~42% less fruit in the famine vines compared with the feast vines, and this difference remained consistent across all three seasons. Fruit from the feast treatment were larger with advanced maturity relative to fruit from control vines; there were no differences in fruit numbers in subsequent seasons. Fruit DMC was higher and maturity was advanced in the ETG vines relative to the control vines. Fruit numbers in the ETG vines consistently increased relative to the control vines each season. There were no consistent treatment effects on fruit mineral concentrations, except that fruit from the feast vines had higher nitrogen concentrations than fruit from the famine vines. Seasonal variation in the incidence of storage disorders was large; in years when disorders were present, physiological pitting incidence was higher in fruit from the treatments that advanced maturity and the incidence of low temperature breakdown was highest in treatments that delayed maturity. Although the treatments affected vine productivity, fruit DMC, and storage performance, there was no evidence of a gradual decline in quality and productivity after 4 years of treatment application.

Kiwifruit growers need to consistently produce high yields of kiwifruit with high DMC to meet consumer preferences for fruit with intense flavor and sweetness (Harker et al., 2009) without compromising storage quality. Mature kiwifruit vines allocate ~50% of annual newly fixed biomass to fruit each season (Boyd et al., 2010; Clark and Smith, 1992). This figure is relatively low compared with some perennial fruit crops; in apples, for example, 70% of annually fixed biomass is allocated to fruit (Heim et al., 1979). The kiwifruit vine is a climbing or straggling plant (Ferguson, 1990) and requires careful canopy management to maintain yields and fruit DMC while controlling canopy vigor. Vine management practices routinely used include trunk girdling, attention to summer pruning, and growing fruit on older, less vigorous wood (Cooper and Marshall, 1991; Davison, 1990; Goren et al., 2004; Miller et al., 2001). A primary aim of these techniques is to minimize competition for resources between fruit and rapidly growing shoots.

Received for publication 5 May 2010. Accepted for publication 24 Jan. 2011.
This project was funded by the Plant & Food Research Kiwifruit Royalty Investment Programme. We thank Tim Holmes and Philip Martin for technical assistance and Mike Currie and Grant Thorp for their helpful suggestions.

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 Treatment application. Each spring (November to December, when mean fruit fresh weight was ≈30 g) fruit counts were carried out on all treatments as a measure of potential vine productivity and so that the control and ETG vines could be thinned to give similar croploads to each other. The adjusted cropload in the control and ETG vines was typically 40 to 50 fruit/m², except in 2006, when the adjusted cropload was nearer 70 fruit/m². In the feast treatment, leaf-to-fruit ratios were kept high by pruning fruiting shoots to approximately six leaves past the last fruit in mid-November and by thinning fruit to one per shoot in December (≈1,500 fruit removed from each vine, cropload reduced from ≈75 to ≈28 fruit/m²). In the famine treatment, leaf-to-fruit ratios were kept low by carrying out little or no spring fruit thinning, removing all non-fruiting shoots in December, and pruning fruiting shoots to one leaf past the last fruit. The pruning and thinning treatments were first applied in late Dec. 2003.

In addition, standard summer pruning was applied to all treatments; unwanted shoot growth was removed at regular intervals (November to March). In the famine treatment, the summer pruning took place 2 weeks later than in the other treatments; this allowed growing shoots to continue to use resources before becoming sources, exacerbating the whole-vine carbohydrate depletion.

The first trunk girdle was applied to the ETG vines each February, ≈120 d after mid-bloom (late summer, first application in Feb. 2004) by removing a 5-mm wide strip of bark from the scion of each vine (Fig. 1). Over fall (March and April), the girdles were reopened as they began to heal. The girdles were then allowed to heal over with the healing occurring in late spring (October to November; Fig. 1). In 2005 (the second season of study), the girdles were not reopened after the initial February girdle because of concerns for vine health and survival.

Fruit sampling and analysis. Fruit were harvested on the same date, when fruit flesh from the famine vines (the latest maturing treatment) had begun to lose their green color (i.e., mean flesh hue angle 103° or less). Two fruit samples were taken from each vine, a 30-fruit sample for fruit quality and mineral nutrient concentration and a 100-fruit sample for storage studies. Fruit quality was assessed by measuring fresh weight (FW), DMC (dry weight as a percentage of FW), soluble solids concentration (SSC), flesh firmness, and flesh hue angle. DMC was determined on a 3-mm thick equatorial slice taken from each fruit and oven-dried at 65 °C for 24 h. SSC was measured with a refractometer (Atago Co. Ltd., Tokyo, Japan) using two drops of juice squeezed from the stem and stylar ends of each fruit combined to give one value per fruit. Flesh firmness was measured on the flat and rounded sides of each fruit using an Effegi penetrometer (Facchini, Alfonsine, Italy) with a 7.9-mm probe after a 1-mm deep slice of skin had been removed. Flesh hue angle was measured using a Minolta chromameter (Minolta, Ramsey, NJ) using a D65 light source after a 2-mm thick layer of skin and flesh had been removed.

Nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were measured on plugs and analyzed. Nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were measured on plugs and analyzed.
of flesh removed from equatorial slices avoiding skin and seeds. The flesh plug samples were combined to give one bulked sample of ≈6 g per vine. The samples were analyzed for N using combustion analysis (vario MAX CN Macro Elemental Analyser; Elementar, Hanau, Germany). The other nutrients were analyzed using nitric acid–perchloric acid digestion followed by inductively coupled plasma–optical emission spectroscopy (Integra XL; GBC, Hampshire IL). Mineral nutrient concentrations were reported on a FW basis. The fruit for storage were placed in single-layer trays lined with polyliners and held at 0 °C for 22 weeks. After this time, disorder incidence was determined by recording the presence of rots and the storage disorders on each fruit.

Three storage disorders were monitored in the fruit (Fig. 2): physiological pitting (recorded when there were more than three individual pits), low temperature breakdown (LTB; recorded when there were three or more regions of brown discoloration each greater than 1 cm²), and hypersensitive marks (recorded when there were at least two areas of dark discoloration greater than 1 cm²) on each fruit.

**Statistical analysis.** Treatments were arranged in a randomized design with 10 vines per treatment. Analysis of variance was carried out using GenStat Release 9.2 PC/Windows XP (Lawes Agricultural Trust Rothamsted Experimental Station, Harpenden, U.K.). Mean separation was carried out using Fisher’s protected least significant difference test and results were reported as different if \( P < 0.05 \). Percentage data were subjected to angular transformation before analysis. Data from each year were analyzed separately.

**Results**

**Fruit numbers and cropload adjustments.** Before any fruit thinning treatments were applied, the ETG vines produced ≈600 to 1200 more fruit per vine than the control vines each year. The ETG vines set 2652 (± 127) fruit per vine in 2005, 3950 (± 179) in 2006, and 2985 (± 254) in 2007 (Fig. 3A). From 2005 to 2007, fruit numbers in the ETG vines ranged from 1163 (± 78) to 1630 (± 240) fruit per vine. The feast vines set ≈1000 more fruit per vine than the ETG vines. The control vines produced similar fruit numbers to the feast vines, except in 2007 when the control vine produced 1741 (± 99) fruit per vine. In 2004, fruit counts were not carried out in the feast and famine treatments. Fruit numbers were lower in both the ETG and control vines in 2007 compared with 2006. This reduction was not seen in the feast and ETG vines and was probably a consequence of the higher croploads retained on the control and ETG vines in 2006 (Fig. 3B).

After fruit thinning, which was part of the treatment application, the ETG vines had the lowest cropload at 750 to 1000 fruit per vine (≈25 to 33 fruit/m²), a removal of ≈40% of the fruit. The croploads of the control and ETG vines were adjusted to ≈45 fruit/m²), a removal of 17% to 40% and 47% to 82% of fruit, respectively. The famine vines received little or no fruit thinning to maintain a low leaf-to-fruit ratio (Fig. 3B).

**Fruit quality at harvest.** Mean FW in the feast vines was consistently 10 to 16 g greater than fruit from the control vines (Fig. 4A). Fruit from the ETG treatment was 8 to 15 g smaller than fruit from the control vines except in 2007, when no difference was detected. The ETG treatment did not affect fruit FW compared with the control fruit except in 2006 when the ETG fruit were 6 g larger than the control fruit. The ETG treatment increased fruit DMC by 0.9% to 1.7% units over the control fruit each year (Fig. 4B). Fruit from the feast vines had higher DMC than the control vines in 2005 and 2007 but not in 2006. Fruit from the ETG vines had lower DMC than the control vines except in 2007 when DMC was the same in the control and ETG vines. Fruit from the ETG vines had higher SSC and firmer, greener flesh (higher hue⁷) than fruit from the other treatments (Figs. 4C–E). Fruit from the ETG and feast treatments generally had higher SSC and softer, more yellow flesh than the control fruit, although these results were not consistent across seasons.

**Fruit mineral concentrations.** Seasonal effects were generally larger than treatment effects, and few consistent treatment effects were observed (Fig. 5). Nitrogen concentrations were consistently higher in the feast fruit than the ETG fruit. Fruit concentrations of K, P, S, Ca, and Mg were generally higher in the ETG fruit than from other treatments (Fig. 5). This effect was not detected in 2005 or 2007. The treatments did not consistently affect fruit concentrations of K, Fe, Zn, Cu, or B (data not presented).

**Fruit storage performance.** There was wide seasonal variation in the proportion of fruit affected by LTB and physiological pitting (Table 1). The incidence of LTB was highest in 2007 with 19% of fruit affected and lowest in 2006 (0.6%). Approximately 5% to 7% of fruit had physiological pitting in 2005 and 2006 with less than 1% incidence in 2007. When LTB was prevalent, fruit from the famine treatment were most severely affected and fruit from the feast and ETG were least affected. Conversely, physiological pitting was more prevalent in fruit from the feast and ETG treatments; fruit from the famine treatment were the least affected. The presence of hypersensitive marks in the fruit showed less extreme seasonal variation with 6.4% to 10.5% of fruit affected each season. In 2006, more hypersensitive marks were visible in fruit from the ETG vines than the remaining vines, and in 2007, both the ETG and famine fruit had higher incidence of hypersensitive marks than the control and feast vines. No treatment effects were detected in 2005 (Table 1).

**Discussion**

After three consecutive seasons, the treatments affected vine productivity, fruit FW and DMC, fruit maturity, and disorder incidence but had inconsistent effects on concentrations of the inorganic nutrients in fruit.

High croploads and partial defoliation reduced return bloom in ‘Hayward’ kiwifruit (Buwalda and Smith, 1990; Cooper and Marshall, 1991). It is therefore not surprising that return bloom was decreased by the famine treatment. The famine vines produced on average ≈1000 (±42%) fewer fruit than the feast vines, a difference that remained relatively consistent between the two treatments.
Unlike the feast and famine treatments, in which and 71% in 2005, 2006, and 2007, respectively. numbers than the control vines, by 25%, 55%, increased shading generated by the higher leaf cropped the control vines). It may be that in- creased shading delayed maturity in ‘Hayward’ ETG vines could carry croploads equivalent the ETG and control vines increased each season. Without thinning to a standard crop- load of $\approx 45$ fruit/m$^2$, it is unlikely that the ETG vines could carry croploads equivalent to 90 to 130 fruit/m$^2$ without seriously compromising fruit size. The ETG and feast treatments increased fruit DMC and advanced maturity relative to fruit from control vines. Fruit maturity attributes are affected by dif- ferent canopy management techniques in a range of crops. Reduced croploads resulted in advanced fruit maturity in apple (Palmer et al., 1997) and peach (Siham et al., 2005). Exces- sive shading delayed maturity in ‘Hayward’ fruit relative to ungirdled controls. In our vines, ETG fruit had higher fruit Ca concentrations compared to the control fruit. Arakawa et al. (1997) re- ported that trunk girdling 40 d after midbloom reduced Ca concentrations in mature apple fruit relative to ungirdled controls. In our vines, the girdle was applied 120 d after midbloom, which is after Ca accumulation in kiwifruit has more or less ceased (Clark and Smith, 1988). It is possible that nutrient uptake was affected by kiwifruit, measured by SSC (Tombesi et al., 1993), whereas more open canopies generated by leader pruning resulted in fruit with higher SSC (Miller et al., 2001). In our famine treatment, a combination of excessive pruning and high croploads resulted in delayed maturity relative to fruit from the control vines. Any advantage conferred by the more open canopy was countered by apparent competition between fruit and the vigorous shoot growth stimulated by the excessive pruning treatment; the result was fruit with lower DMC.

The incidence of physiological pitting and LTB was associated with fruit maturity at harvest. Fruit from treatments that were more mature at harvest were more likely to develop physiological pitting, and fruit that were less mature at harvest were more likely to develop LTB. This supports previous findings by Clark et al. (2004) that fruit that were affected by LTB contained less dry matter, had appreciably lower SSC, and greener flesh color than their unaffected counterparts. In this experiment, we did not harvest each treatment at the same maturity; this approach could offer additional insight into fruit maturation effects. There was no evidence that fruit concentrations of inorganic nutrients were associated with either LTB or pitting incidence despite previous findings with ‘Hayward’ kiwifruit that low fruit Ca concentrations were associated with the incidence of both physiological pitting (Ferguson et al., 2003) and LTB (Gerasopoulos and Drogoudi, 2005).

Hypersensitive marks are areas of cell death that form at the point of pathogen ingress and which correlate with the exhibition of resistance (Mur et al., 2007). In kiwifruit, hypersensitive marks appear to be linked to a range of factors, including insect damage, sunburn, and rots. We found no association between the incidence of hypersensitive marks and fruit maturity at harvest. In 2007, for example, the ETG and famine fruit had higher incidence of hypersensitive marks. Skin damage caused by the treatment application (leaf removal in the famine treatment) combined with the higher degree of sun exposure experienced by fruit from the ETG and famine fruit may be partly responsible for the higher inci- dence of hypersensitive marks in these two treatments.

We expected that long-term application of ETG or famine-type treatments would impair root function by affecting root reserves or root turnover, thereby reducing the root uptake of water and soil nutrients. After 3 years, we have seen no evidence of decline in fruit nutrient concentrations and little evidence of treatment-induced differences in fruit nutrient status with the exception that N concentrations were consistently lower in the famine fruit than the feast fruit. Arakawa et al. (1997) re- ported that trunk girdling 40 d after midbloom reduced Ca concentrations in mature apple fruit relative to ungirdled controls. In our vines, the girdle was applied 120 d after midbloom, which is after Ca accumulation in kiwifruit has more or less ceased (Clark and Smith, 1988). It is possible that nutrient uptake was affected by...
The treatments but was expressed in other parts of the vine such as leaves. We conclude that whole-vine treatments that allocate a greater proportion of carbohydrates to fruit than to root or shoot growth also affect vine productivity and fruit quality. Extended trunk girdling produced fruit with higher DMC and typically advanced maturity compared with ungirdled control vines carrying the same cropload and harvested on the same date. Fruit from the ETG vines were more susceptible to physiological pitting and less susceptible to LTBP than fruit from the control vines. Each season the ETG vines produced lower croploads and higher leaf-to-fruit ratios, and famine (whole vine carbohydrate depleted by maintaining high croploads and excessive, poorly timed pruning).

**Table 1. Effect of vine management treatments on fruit storage disorders in ‘Hort16A’ kiwifruit.**

| Treatment¹ | Low temp breakdown | Physiological pitting | Hypersensitive marks |
|------------|-------------------|----------------------|----------------------|
| Control    |                   |                      |                      |
| ETG        |                   |                      |                      |
| Feast      |                   |                      |                      |
| Famine     |                   |                      |                      |

¹Control = standard orchard practices; ETG = extended trunk girdling where vines were girdled in late summer and the girdle reopened over winter; feast = minimal depletion of carbohydrate reserves by low croploads and high leaf-to-fruit ratios; and famine (whole vine carbohydrate depleted by maintaining high croploads and excessive, poorly timed pruning).

Different letters within columns denote significant differences among means (Fisher’s protected least difference test, P < 0.05).

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