Evaluation of rootstock and crop load effects on the performance of `Gibson Golden Delicious' and three scab-resistant apple cultivars

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Evaluation of rootstock and crop load effects on the performance of ‘Gibson Golden Delicious’ and three scab-resistant apple cultivars

by

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A thesis submitted to the graduate faculty in partial fulfillment of the requirements for the degree of

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ABSTRACT

At the beginning of the 20th century, Iowa ranked sixth in national apple production. Iowa currently provides about 15 percent of the 1.3 million bushels of fresh apples eaten by Iowans annually (Pirog, 1999) and is ranked at 28th in the nation in production. The reduction in rank was mostly due to the Armistice Day freeze that killed many apple trees in 1940. Given the time needed to establish an orchard and mechanization of grain crops, many farmers changed to corn and soybeans that are less vulnerable to low temperature injury. However, current changing economic conditions and food sourcing policies are prompting farmers to consider crop diversification including apple production (Pirog, 1999). Iowa’s apple industry is affected by production challenges such as selection of good quality rootstocks and crop load management for high quality fruit and consistent apple production across growing seasons. The primary objective of this investigation was to evaluate the effect of rootstocks and cropping densities on fruit quality attributes and return bloom of ‘Gibson Golden Delicious’ apples’ and three apple scab-resistant cultivars (Redfree, Liberty, and GoldRush).

Two field research studies were conducted at the Iowa State Horticulture Research station near Ames, Iowa. The first experiment was conducted in an established ‘Gibson Golden Delicious’ apple (Malus ×domestica Borkh.) orchard to evaluate the effects of dwarfing rootstocks under different crop load levels on tree growth, yield, fruit quality, and return bloom. Treatments included five dwarfing rootstocks and trees that were hand thinned to crop loads ranging from 3 to 13 fruits per cm² trunk cross-sectional area. In the second experiment, all the three apple scab-resistant cultivars (Redfree, Liberty, and GoldRush) were grown on ‘Malling 9 T337’ (M.9 T337) rootstock and were hand thinned to crop loads ranging from 3 to 13 fruits per cm² trunk cross-sectional area. Fruit quality tests (size distribution, starch content,
fruit skin color, flesh firmness, and soluble solids) were measured at harvest and after 60 d of refrigerated storage for experiment one and for ‘GoldRush’ apples in experiment two. Fruit quality attributes for Redfree and Liberty were measured only at harvest in experiment two because these cultivars are stored for a short duration only. From the first experiment, ‘Cornell-Geneva 3041’ and ‘Budagovsky 62-396’ are promising rootstocks based on the higher percentage of marketable fruit and soluble sugar content. Results from both studies indicate that high crop densities increased yield but reduced the fruit quality attributes. The optimum crop load for a high yield with the highest percentage of marketable fruit was 6 – 8 fruits per cm$^2$ of trunk cross-sectional area.
CHAPTER 1. GENERAL INTRODUCTION

Thesis Organization

The following thesis consists of four chapters. Chapter one provides a general introduction to the studies and includes a review of current literature pertinent to these investigations. Chapters two and three are presented as manuscripts to be submitted to the Journal of the American Pomological Society. General conclusions for both studies are provided in chapter four.

Introduction

The Iowa apple crop in 1909 was 6.7 million bushels, ranking Iowa sixth in U.S apple production (Pirog, 1999). Iowa apple production reached a historical peak of 9.5 million bushels in 1911 and remained a top apple producing state in the early 1920’s through the 1930’s after which production started to decline. The decrease was due to the increased grain production in Iowa and greater apple production from other competing states, like Washington, Michigan, and New York (Pirog, 1999). The Iowa apple industry was impacted by a severe freeze on 11 November (Armistice Day) in 1940 which injured and killed many trees. Apple production in 1941 was 15% of the 1940 crop (Pirog, 1999). Many apple growers decided not to replant their orchards and the apple industry dwindled in its economic importance to Iowa. Iowa apple production further declined as Washington, Michigan, and New York increased production and developed the appropriate storage facilities, marketing capabilities, and distribution and sales infrastructure to successfully ship apples to Iowa and other states.
Recently the Iowa apple industry has been growing with a steady increase and in 2010 the production was at 4.1 million pounds with total revenue of 2.1 million dollars (Anon. 2009). As the industry regains momentum, it also faces challenges such as suitable rootstocks and fruiting cultivars, pests and disease management, and optimal crop load management (Pirog, 1999). Over the years rootstocks were developed with good root anchorage and disease resistance, less suckering, and high precocity (Russo et al., 2007). New apple cultivars that are resistant to apple scab, which is a major disease of apples in the Midwest (Crosby et al., 1994), have been released, but information is not available about their cropping capacities and how the crop load affects yield and fruit quality variables.

The study was undertaken to evaluate the influence of rootstocks and crop load on tree and fruit growth, fruit quality attributes, and return bloom. The first experiment evaluated five dwarfing rootstocks and different crop load levels on ‘Gibson Golden Delicious’ apples. The second experiment investigated the relationship between crop load and tree growth, yield, and fruit quality variables of ‘Redfree’, ‘Liberty’, and ‘GoldRush’.

**Literature Review**

*Apple cultivars*

The apple (*Malus ×domestica* Borkh.) cultivars evaluated in this study were Gibson Golden Delicious and three scab resistant apple cultivars, Redfree, Liberty, and GoldRush. ‘Golden Delicious’ was a chance seedling, perhaps of ‘Grimes Golden’, and introduced in 1914. Its flavor is sweet, spicy and moderately acidic. It is firm at harvest and tends to soften in storage. It has a tender skin and golden yellow to greenish yellow skin color with a tendency to russet and has a yellowish white flesh (Baugher and Blizzard, 1987). ‘Redfree’ is a high-finish
red apple with field immunity to apple scab disease. The fruits have a smooth glossy skin, with 80-90% of the skin medium washed to slightly striped red in a yellow background (Williams et al., 1981). ‘Liberty’ resulted from a cross, ‘Macoun’ × Purdue 54-12, made in 1955 and the cultivar was named in 1978. The fruit has a deep, dark red, background color and the flesh is yellowish, juicy, crisp, and with a good subacid flavor (Lamb et al., 1978). ‘GoldRush’ was released in 1994, derived from a cross made in 1972 of ‘Golden Delicious’ as the seed parent with Co-op 17 (PRI 1689-110) as pollen parent (Crosby et al., 1994). The fruit is characterized by a complex, spicy flavor with high degrees of acidity and sweetness. It is firm, a low-ethylene producer, and a long-storage apple. It is a late-maturing apple with yellow gold ground color (Janick, 2001). The maturity season (harvest time) for ‘Redfree’ is 12 - 20 Aug., 20 - 27 Sept. for ‘Liberty’ and ‘Gibson Golden Delicious’, and 20 - 30 Oct. for ‘GoldRush’ apples (Baugher and Blizzard, 1987; Crosby et al., 1994; Lamb et al., 1978; Williams et al., 1981).

Dwarfing rootstocks

Rootstocks are widely used to control the growth and hasten precocity of selected apple fruiting cultivars. Dwarfing rootstocks can result in production of more fruit per length of lateral shoot resulting in high yields (Parry and Rogers, 1972; Robitaille and Carlson, 1976). Rootstocks can also influence tree size, fruit quality, yield efficiency, mineral uptake, and tree performance under adverse environmental conditions (Fallahi et al., 2002). Five dwarfing rootstocks were evaluated for their effects on fruit quality attributes and return bloom after adjusting for crop load. ‘Geneva 16’ (G.16) resulted from a cross between Ottawa 3 and Malus floribunda and was introduced by the New York State Experimental Station, Geneva, NY. It is resistant to fire blight and precocious with good productivity (Robinson et al., 2006). ‘Cornell-
Geneva 3041’ (CG. 3041) is dwarfing and highly productive (Robinson et al., 2002). ‘Budagovsky 62-396’ (B.62-396) was released from the apple breeding program in Russia and has good resistance to crown rot and woolly apple aphids (Russo et al., 2008), and is very dwarfing and precocious. ‘Malling 9 T337’ (M.9 T337) and ‘Malling 26’ (M.26) are dwarfing rootstocks from the Malling apple breeding program in England. They have poor resistance to fire blight, but have good precocity (Marini et al., 2009).

**Crop load management**

Crop load is a measure of the fruiting density that is typically expressed as the number of fruits per cm² of trunk cross-sectional area (Stover et al., 2004; Wunsche and Ferguson, 2005). Crop load management refers to adjusting the number of fruits per tree. Reducing the crop load before or during bloom maximizes fruit growth and development in the current season and following year. Typically, the longer that unwanted fruits remain on the tree, the greater the negative effect they will have on fruit size, tree growth, flower bud differentiation, flower bud hardiness, the next season’s cropping potential, and tree survival (Byers and Marini, 1994; Schmidt et al., 2009). Commercial apple growers cannot afford to have fruit trees bear fruit biennially or produce undersized fruit. Thinning of fruit is therefore employed to improve fruit size, quality, and regulate cropping. Biennial bearing habits in apple can result in high yields of small, poor quality fruit in the year of bearing and in the next season, low yields of large fruits prone to physiological disorders with minimal yield (Singh, 1948). Fruit thinning is the most important technique in apple cultivation that improves fruit quality (Looney, 1993). In commercial apple production thinning is used to increase size, enhance return bloom and production and lessen biennial bearing and avoid limb breakage (Byers et al., 1990; Ferree,
1996; Williams, 1979). Fruit size, appearance, flavor, firmness, and storability are very important qualities for the fresh market and may be enhanced with crop load regulation.

**Tree and fruit growth and development**

The ratio of fruit yield to tree size (yield efficiency) reflects the efficiency with which the products of photosynthesis are partitioned between crop and vegetative growth. Tree growth can be quantified as an increase in trunk cross-sectional area measured in cm$^2$ while tagged fruits can be measured throughout the entire growing season to determine the rate of fruit growth overtime (Lakso et al., 1998). Westwood and Roberts (1970) reported that the correlation between trunk cross-sectional area (TCSA) and the production potential of a tree is affected by different management and pruning regimes. Fruit thinning can improve the leaf to fruit ratio by increasing the leaf area available to the remaining fruits (Forshey, 1986; Koike et al., 2003).

**Crop load management in relation to fruit quality attributes**

Crop load management is carried out by either flower or fruit thinning and this practice is essential in commercial apple production to improve fruit size and fruit quality characteristics (starch content, soluble solids content, firmness, skin color) (Wertheim, 1997). Fruit size has been reported to be negatively correlated to the number of fruits per tree and positively correlated to leaf area available per fruit (Palmer et al., 1997). Therefore, crop load regulation in apples is important to improve consistency in production and fruit size and increase fruit quality (Stover et al., 2004).

Fruit quality attributes, like soluble solids content and firmness, can be affected by crop load in apples where less crop results in larger apples with storage disorders; heavily cropped trees produce hard, small-sized apples (Forshey and Elfving, 1989). Starch changes to sugars as
the apple fruits ripen and this hydrolysis begins from the core of the fruits progressing outwards (Little, 1999; Chennell et al., 2002). As apples ripen, the cementing materials (middle lamella) disintegrate. Firmness will decrease as the fruit maturity progresses and will continue to fall in storage (Harker et al., 1997).

As apples mature, starch is converted to sugars. The rise in sugars makes the fruits sweeter and more desirable to the consumers (Kingston, 1992). Sugar content (composed of 2.1% sucrose, 2.4% glucose, and 5.9% fructose) is a major component of the soluble solids in apple fruits (Wills et al., 1989) and soluble solids usually increase as the fruits ripen (Blankenship and Unrath, 1988). Fruit skin color is the most obvious change that occurs during fruit maturation in many apple cultivars. Most consumers use color as a major criterion to determine the ripeness of apples and make the decisions on which ones to purchase (Moskowitz and Krieger, 1993). The color of apples is determined mainly by the amounts of pigments in the fruit skin such as anthocyanins, chlorophylls, and carotenoids (Saure, 1990). These pigments undergo considerable changes during fruit development; chlorophyll gets degraded in fruits that turn yellow or red at maturity and chloroplasts change to chromoplasts. ‘Golden Delicious’ apples will change from green to yellow as they reach maturity and this change is primarily associated with a reduction in chlorophyll concentration and an increase in xanthophylls (Workman, 1963). Both ‘Redfree’ and ‘Liberty’ will change from green to red skin color as the fruits mature due to an increase in the anthocyanins pigments towards ripening. Color change in ‘GoldRush’ apples is from green to yellow at harvest and this is due to an increase in xanthophylls (Crosby et al., 1994; Williams et al., 1981).
Return bloom

Forshey and Elfving (1997) recommended that crop load should be limited to the minimum number of fruits on a tree that will ensure acceptable fruit quality and adequate return bloom for a full crop in the subsequent growing season. The following season’s flower buds are initiated early in the fruit development of the current growing season and these two processes are competitive where excessive fruit will inhibit flower bud formation for the next season (Koutinas et al., 2010). Fruit thinning will improve the quality of the current season’s fruit as well as the fruit numbers and size during the subsequent growing season (Forshey, 1986).

For Iowa apple growers to maintain a sustainable fruit production enterprise, further research on the performance of dwarfing rootstocks with varying crop loads is needed to determine their cropping capacities. New rootstock selections should be compared to standard selections available in the industry. Information on how to manage new scab-resistant fruiting cultivars regarding optimal crop load and its effects on yield, growth and development, and quality variables is important for adoption of profitable and environmentally sound apple cultivars that contribute to sustainable production.

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CHAPTER 2. ROOTSTOCK EFFECTS ON TREE AND FRUIT GROWTH, YIELD, FRUIT QUALITY ATTRIBUTES, AND RETURN BLOOM OF ‘GIBSON GOLDEN DELICIOUS’ APPLES AFTER ADJUSTING FOR CROP LOAD

A paper to be submitted to the Journal of the American Pomological Society

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ADDITIONAL INDEX WORDS. *Malus* ×*domestica*, soluble solids, flesh firmness, fruit skin color, hue angle, lightness, yield efficiency, TCSA

Abstract

The influence of five dwarfing rootstocks on yield, fruit quality attributes, and return bloom of ‘Gibson Golden Delicious’ apples (*Malus* ×*domestica* Borkh.) was evaluated during the 2010 and 2011 growing seasons. Trees were grafted on ‘Malling 26’, ‘Malling 9T337’, ‘Geneva 16’, ‘Cornell-Geneva 3041’, and ‘Budagovsky 62-396’. The study was conducted at the Iowa State University Horticulture Research Station near Ames, Iowa, and trees were hand-thinned to crop loads ranging from 3-13 fruits per cm$^2$ of trunk cross-sectional area. Data were analyzed using analysis of covariance with crop load as the covariate. Rootstock affected tree growth, yield, fruit weight, soluble solids and firmness at harvest. Soluble solids content, fruit weight, and return bloom decreased for all the rootstocks at increasing crop load levels. A crop load level of 6 – 8 fruits per cm$^2$ of trunk cross-sectional area was the optimum range for high yield with fruit size greater than 68 mm. Trees grown on G.16 had the lowest yield and smallest apples.
Introduction

The North American apple industry is in a transition from relatively low-density plantings based on semi-dwarfing rootstocks to high-density plantings based on fully dwarfing rootstocks that provide more efficient training systems and promote earlier production and reduced inputs (Robinson et al., 2004). The economic success of high-density orchards requires rootstocks that control tree size, promote precocity, are capable of producing high yields, remain productive for the life of the orchard, produce high-quality fruit, and tolerate biotic and abiotic stresses (Crassweller et al., 1989; Robinson et al., 2004). ‘Golden Delicious’ apples are versatile and appealing fruits of widespread popularity (Baugher and Blizzard, 1987). It is the second-most widely grown apple in the U.S., and the interest of growers has increased overtime (Perez and Pollack, 2008). This cultivar is prone to biennial bearing, a phenomenon caused by high crop loads during one growing season followed by low yield in the next season (Davis, 1957; Forshey and Elfving, 1976). Rootstocks are the foundation of the orchard (Autio et al., 2003; Barritt, 2000), and they remain key to the design of profitable high-density orchard systems (Perry and Byler, 2001). Rootstocks need to be evaluated for their adaptation, size control, and ability to produce early crops of sufficient yield with quality fruit. As crop load increases, fruit size decreases, fruit maturity is delayed, and the ability of the tree to initiate floral primordia for the next crop declines (Denne, 1963).

Rootstock and crop load influence cropping potential (Hampson et al., 2004; Perry and Byler, 2001; Robinson et al., 2004), bud development and flowering (Conrod et al., 1996; Hirst and Ferree, 1995; Warmund et al., 2002), and aspects of fruit quality such as ripening and storage capability (Autio et al., 1996; Lord et al., 1985), fruit size (Marini et al., 2002) and firmness (Brown and Wolfe, 1992). Rootstocks effects were not consistent from
site to site or cultivar to cultivar and varied overtime. Autio (1991) documented that fruit size of ‘Starkspur Supreme Delicious’ planted in Massachusetts was affected by rootstock. However, Hirst and Flowers (2000) found no effect of rootstock on the rate of fruit growth or final fruit size of ‘Gala’ apples grown in Indiana. Rootstock effects on apple fruit quality need to account for variations in crop loads. Analysis of co-variance can be used to remove variations in yield, fruit quality attributes, fruit and tree growth, and return bloom due to crop load or number of fruits per cm$^2$ of trunk cross-sectional area (TCSA) (Marini et al., 2002).

There is limited information about the influence of new fully dwarfing rootstock and crop load on ‘Golden Delicious’ apple fruit quality and return bloom. The objective of the study was to evaluate the horticultural performance of five size-controlling rootstocks after adjusting for crop load on yield, fruit quality attributes, fruit and tree growth, and return bloom.

**Materials and Methods**

*Experimental site, plant material, and treatments*

This research was conducted at the Iowa State University Horticulture Research Station near Ames, IA (lat. 42°10’06”N, long. 93°64’09”W), during the 2010 growing season and 2011 bloom period. The experimental site was a seven-year-old orchard trained to a vertical axis system with ‘Gibson Golden Delicious’ grafted onto the following rootstocks: ‘Malling 9 T337’ (M.9 T337), ‘Geneva 16’ (G.16), ‘Malling 26’ (M.26), ‘Cornell-Geneva 3041’ (CG.3041), and ‘Budagovsky 62-396’ (B.62-396). Trees were intercropped with ‘Pacific Gala’/B.9 to serve as the pollinizer. Trunk circumference of each tree was measured 25 cm above the graft union and was then used to calculate the trunk cross-sectional area as described
by Strong and Azarenko (2000) and Westwood and Roberts (1970). Trees on the different rootstocks were manually adjusted to varying crop loads. The crop load ranged from 3 to 13 fruits per cm$^2$ of TCSA, as a continuous variable, and was separated into four crop load levels of 3, 6, 9, and 12 fruits per cm$^2$ of TCSA. Crop loads were randomly assigned to the individual trees within a rootstock.

The soil was primarily a Nicolette loam (fine loamy, mixed, superactive, mesic Acquic Hapludolls) (USDA, 1984). Standard orchard production practices (trickle irrigation, nutrient supply, and pests and disease management) were uniform across all experimental units (Lewis et al., 2009).

Rate of fruit growth

Fourteen days after full bloom (DAFB), fruits were hand-thinned, and thinning was completed within 21 DAFB to randomly adjust the number of fruits per tree to the desired treatment crop loads. Fruit diameter was recorded weekly starting on 23 June (32 DAFB) of five fruits randomly tagged from the lower, middle, and upper parts of each tree’s canopy with a digital hand-caliper (Digimatic, Model 50-321, Mitutoyo, Co., Japan) up to 136 DAFB.

Tree growth

Trunk circumference was measured late in spring 2010 (13 April) to determine TCSA for treatment allocation and measured again in the fall (12 October) after harvesting was completed to obtain TCSA for computing yield efficiency. The difference in spring and fall 2010 TSCA was used to evaluate differences in tree growth for all the treatment trees used in the study.
Yield and fruit quality attribute measurements

The fruits were harvested and weighed at 150 DAFB. The fruits were sized on a rotary Greefa A3 apple sizer (Model 86637, Type 3, Greefa Co., Utrecht, The Netherlands) and counted for seven size categories. The seven fruit size categories included, ≤ 57 mm, 58 mm - ≤ 63 mm, 64 mm - ≤ 70 mm, 71 mm - ≤ 76 mm, 77 mm - ≤ 83 mm, 84 mm - ≤ 89 mm, and > 89 mm. The total weight and fruit number per tree were used to compute average fruit weight. Six apples within the average fruit size per tree were randomly selected and evaluated for the fruit quality attributes of starch pattern index, firmness, soluble solids content, and fruit skin color. Starch pattern index was determined by cutting fruits at the equator and dipping them into iodine solution for two minutes and then rating the starch disappearance pattern (stained fruit tissue) based on a standard color chart as described in Brookfield et al., (1997) and Fan et al., (1995).

Flesh firmness was measured using a Universal Instron Testing Machine (Model 5566, Instron Corporation, Norwood, MA, USA) as the force in Newtons required to penetrate the fruit tissue to a depth of 7.9 mm using a Magness-Taylor round penetration probe, 11.1 mm in diameter at a penetration rate of 24 mm per minute (Abbott et al., 1976). Two penetrations on opposite sides of each whole, unpeeled fruit were made and the values averaged to obtain the firmness values. A digital, temperature-compensated refractometer (Atago Co., Tokyo, Japan) was used to determine the soluble solids content of juice extracted from homogenized slices from opposite sides of each fruit using a fruit blender as described by Mitcham and Kader (1996). All the fruit quality tests were completed with three days after harvest and during this period fruits were held in 4.54 kg-size drawstring, vented
polyethylene bags (Monte Package Co., Riverside, MI) and refrigerated storage of 3.3°C and maintained at 95% relative humidity.

Fruit skin color was measured using a bench top Hunter LabScan XE colorimeter (Hunterlab, Reston, VA) using Commission Internatioanle d’Eclairage (CIE) illuminant D65, 10° standard observer, and port size of 40 mm. The colorimeter was calibrated using black and white tiles and used CIE L*a*b* color space coordinates (where L* value corresponds to a dark-bright scale of 0-100; 0=black and 100=white, a* is negative for green and positive for red; b* is negative for blue and positive for yellow). Chroma was computed using (a*² + b*²)⁰.⁵ and hue angle was determined as the arc-tan of (b*/a*) as described by McGuire (1992). For each fruit, color values were measured at both the reddest and the greenest points of the fruit equator.

Six fruits per tree were placed in 4.54 kg-size drawstring, vented polyethylene bags. All the above fruit quality attributes (firmness, soluble solids content, and fruit skin color) were obtained on apple fruits that were held in refrigerated storage for 60 d at 3.3°C and maintained at 95% relative humidity. The two month storage was located at the Iowa State University Horticulture Research Station.

Return bloom was determined by counting the number of flower clusters per tree during the 2011 bloom period (10 May).

Statistical analysis

The experimental design was a Completely Randomized Design with rootstock as a treatment. Crop load was a continuous variable and analysis of covariance (ANCOVA) was used. Mean separation for the adjusted rootstock means was performed using PDIFF. Mean separation for the estimated crop load means was determined using PDIFF and the separation
conducted within crop loads among all rootstocks (Littell et al., 2006; Marini et al., 2002; Miliken and Johnson, 2002).

**Results**

Rootstock did not affect fruit growth as measured by fruit diameter during the growing season after adjusting for crop load (Fig. 1). Trees on M.26 had more of an increase in TCSA than trees on G.16, CG.3041, and B.62-396 rootstocks (Table 1). Trees on M.26 had a higher yield compared to those on CG.3041, and B. 62-396 rootstocks. There were no differences in yield efficiency for all the trees on the five rootstocks. Trees on B.62-396 had a higher average fruit weight compared to those grown on the other four rootstocks. Trees on M.9T337, CG 3041, and B. 62-396 had a higher percentage of fruits that were greater in size than 68 mm when compared to those on G.16 but they did not differ from those grown on M.26. Trees on M.26 resulted in a higher return bloom (number of floral clusters) when compared to those grown on CG.3041 and B.62-396, but no differences occurred for number of flower clusters per cm$^2$ of TCSA. Rootstocks did not affect yield efficiency and number of flower clusters at the crop loads of 3, 6, 9, and 12 fruits per cm$^2$ of TCSA (Appendix Table 1).

At harvest, fruits from trees grown on M.9T337 and CG.3041 had a higher starch score indicating lower starch content compared to those from M.26 and G.16 (Table 2). Fruits from trees grafted on B.62-396 had higher sugar content from those grown on G.16 and M.26 at harvest. Apples from trees grown on CG.3041 and B.62-396 were less firm compared to apples from the other three rootstocks.

Increase in tree trunk circumference was greater for trees grown on M.26 only at a crop load level of 6 fruits per cm$^2$ of TCSA compared to other rootstocks (Table 3). Yield (total fruit
weight) for trees on M.26 was greater than that of B.62-396 at a crop load levels of 3 and 6 fruits per cm$^2$ of TCSA. No differences tree growth and yield were observed among all rootstocks at crop load levels of 9 and 12 fruits per cm$^2$ of TCSA.

Differences among rootstocks for average fruit weight were observed at the crop load level of 6 fruits per cm$^2$ of TCSA with trees grown on M.26, CG.3041, and B.62-396 rootstocks having higher fruit weight compared to those grown on M.9 T337 (Table 4). At a crop load level of 6 fruits per cm$^2$ of TCSA trees grown on M.26, CG.3041, and B.62-396 had a higher percentage of fruits greater than 68 mm (marketable fruit) when compared to trees grown on M.9 T337. No differences were observed among M.26, M.9 T337, and G.16 rootstocks for average fruit weight and percentage of marketable fruit at crop load levels of 9 and 12 fruits per cm$^2$ of TCSA.

Trees grown on CG.3041 had a higher starch score value indicating less starch in the fruit flesh when compared to fruits from trees grown on the other four rootstocks at a crop load of 3 fruits per cm$^2$ of TCSA (Table 5). At crop load level of 3 fruits per cm$^2$ of TCSA fruits from trees grown on CG.3041 and B.62-396 had a greater amount of soluble solids content compared to those from trees on M.26. Return bloom as measured by flower clusters per tree or flower clusters per cm$^2$ of TCSA was not affected by rootstock (Appendix Table 2).

Differences in fruit firmness at harvest were observed at crop load levels of 3 and 6 fruits per cm$^2$ of TCSA with fruits from trees grown on M.26 and G.16 being more firm than those on CG.3041 and B.62-396 rootstocks. No differences were observed among rootstocks for apple fruit skin color variables at harvest. Rootstock did not affect soluble solids content, firmness, and color variables 60 days after refrigerated storage. (Table 6 and Appendix Tables 3, 4, 5, 6, and 7).
Discussion

Autio et al., (2006) and Autio and Krupa (2001) found that trees on M.26 were the largest when compared to P.16, P.2, B.491, and B.469 rootstocks; our findings showed that trees grown on G.16, CG.3041, and B.62-396 rootstocks had a smaller size when compared to trees grown on M.26 rootstock. Yield is related to tree size with larger trees having the greatest yield but smaller yield efficiency (Elfving and Schechter, 1993) and trees on M.26 had greater yield than trees on CG.3041 and B.62-396. Trees on CG.3041, B.62-396, and M.26 had a greater fruit weight and percentage of marketable fruit compared to the M.9 T337 rootstock probably due to their increased dwarfing abilities and subsequent effects on the growth and development of the scion canopy (Forshey and Elfving, 1977). Autio and Krupa (2001) found differences among rootstock effects on yield and tree growth when working on ‘Ginger Gold’ apple trees with M.9 and Mark rootstocks performing better than the Vineland and Polish series rootstocks. The fruit growth curves for ‘Gibson Golden Delicious’ were similar to those obtained by Al-Hinai and Roper (2004) for ‘Gala’ apples.

The high soluble solids and low firmness values of apples from trees grown on CG.3041 and B.62-396 rootstocks could have been caused by an ability for early maturity from these rootstocks, and thus apples from these trees could be harvested slightly early. Brown and Wolfe (1992) working with ‘Stark Supreme Delicious’ apple trees found that apples from trees grown on more dwarfing rootstocks had a higher sugar content compared to the semi-dwarf rootstocks.

The covariance approach to determine rootstock effects on the yield, fruit quality attributes, and return bloom allows estimation of means for each rootstock at increasing crop loads (covariate). This information can allow researchers to determine the performance of
rootstocks under different crop loads. Differences in fruit size among rootstocks at a crop load level of 6 fruits per cm\(^2\) of TCSA could have been due to competition for assimilates and limited number of leaves per fruit numbers, but there were no differences observed at the higher crop load levels of 9 and 12 fruits per cm\(^2\) of TCSA. The lack of rootstock effect on fruit skin color variables of lightness and hue angle could have been due to the training system and orchard pruning. The trees in the study were adequately pruned in the spring, trained on a vertical trellis axis, and established on dwarfing rootstocks; these factors could have improved light interception in the canopies during the growing season and thus the lack of rootstock effect on apple fruit hue angles both at harvest and after storage.

**Conclusion**

Trees grown on G.16, CG.3041, and B.62-396 were smaller in size and these rootstocks were more dwarfing compared to the Malling series tested in the study. Fruit yield was highest for larger trees grown on M.26 rootstock. Fruit weight was greatest for apples from trees grown on M.26, CG.3041, and B.62-396 rootstocks at a crop load level of 6 fruits per cm\(^2\) of TCSA. At harvest, B.62-396 had the highest amount of soluble solids while fruits from trees grown on CG.3041 were the least firm. Rootstocks did not have an effect on fruit firmness and soluble solids content after 60 days of refrigerated storage. Trees on M.9 T337 resulted in small sized apples both in terms of fruit weight and percent of fruits greater than 68 mm. Generally, the optimal crop load ranged from 6 – 8 fruits per cm\(^2\) of trunk cross-sectional area for a high fruit size (fruit weight and percentage of fruits greater than 68 mm), fruit quality attributes (firmness and soluble solids). Trees on M.26 had a smaller number of flower clusters during the second growing season.
Based on the results from this study, apple growers in Iowa should consider growing ‘Gibson Golden Delicious’ on CG.3041, G.16, and B.62-396 and managing trees to a crop load range of 6 – 8 fruits per cm$^2$ trunk cross-sectional area for optimal yields, marketable fruit size, and fruit quality attributes.

**Literature Cited**


Table 1. Effects of rootstock on tree growth, yield, fruit size, and return bloom of ‘Gibson Golden Delicious’ apple trees.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Increase in TCSA (cm²)</th>
<th>Yield (kg)</th>
<th>Yield efficiency (kg cm⁻²)</th>
<th>Average fruit wgt. (g)</th>
<th>Fruits &gt; 68 mm (%)</th>
<th>Flower clusters per tree x</th>
<th>Flower clusters/cm² of TCSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>M.26</td>
<td>24.9 a</td>
<td>36.5 a</td>
<td>0.58 a</td>
<td>168 b</td>
<td>59 ab</td>
<td>362 a</td>
<td>6 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>16.8 ab</td>
<td>32.2 ab</td>
<td>0.65 a</td>
<td>175 b</td>
<td>66 a</td>
<td>280 ab</td>
<td>6 a</td>
</tr>
<tr>
<td>G.16</td>
<td>12.3 b</td>
<td>29.9 ab</td>
<td>0.67 a</td>
<td>159 b</td>
<td>45 b</td>
<td>305 ab</td>
<td>7 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>8.9 b</td>
<td>28.3 b</td>
<td>0.72 a</td>
<td>173 b</td>
<td>66 a</td>
<td>254 b</td>
<td>6 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>11.1 b</td>
<td>22 b</td>
<td>0.68 a</td>
<td>228 a</td>
<td>68 a</td>
<td>238 b</td>
<td>8 a</td>
</tr>
</tbody>
</table>

*Means followed by the same letter within columns are not different according to PDIF at a P value ≤ 0.05.

*All values for the different response variables are adjusted means obtained after taking into account the effects of crop load.

*Flower clusters were counted during spring bloom period of 2011 to determine return bloom.
### Table 2. Effects of rootstock on starch, soluble solids, and firmness of ‘Gibson Golden Delicious’ apples at harvest and after 60 d of refrigerated storage.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>At harvest</th>
<th></th>
<th></th>
<th>After 60 d of refrigerated storage</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Starch&lt;sup&gt;z&lt;/sup&gt;</td>
<td>Soluble solids</td>
<td>Firmness (N)&lt;sup&gt;y&lt;/sup&gt;</td>
<td>Soluble solids</td>
<td>Firmness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>content (%)</td>
<td></td>
<td></td>
<td>content</td>
<td>(N)</td>
<td></td>
</tr>
<tr>
<td>M.26</td>
<td>2.8 b&lt;sup&gt;w&lt;/sup&gt;</td>
<td>11.8 b</td>
<td>91.6 a</td>
<td>15.9 a</td>
<td>49.4 a</td>
<td></td>
</tr>
<tr>
<td>M.9 T337</td>
<td>3.0 a</td>
<td>12.3 ab</td>
<td>87.9 a</td>
<td>15.7 a</td>
<td>52.3 a</td>
<td></td>
</tr>
<tr>
<td>G.16</td>
<td>2.7 b</td>
<td>11.7 b</td>
<td>91.2 a</td>
<td>15.8 a</td>
<td>52.9 a</td>
<td></td>
</tr>
<tr>
<td>CG.3041</td>
<td>3.3 a</td>
<td>12.2 ab</td>
<td>79.8 b</td>
<td>15.6 a</td>
<td>50.6 a</td>
<td></td>
</tr>
<tr>
<td>B.62-396</td>
<td>2.9 ab</td>
<td>13.3 a</td>
<td>78.9 b</td>
<td>16.1 a</td>
<td>49.2 a</td>
<td></td>
</tr>
</tbody>
</table>

<sup>z</sup> Starch pattern index is an index of starch disappearance in the flesh and was based on a scale of 1-9 at the time of harvest where 1 indicates starch throughout the flesh and 9 no starch in the flesh.

<sup>y</sup> Newton is a unit of force and 1 kilogram force x 9.81= Newton

<sup>x</sup> Means followed by the same letter with in columns are not different according to PDIFF at a P value ≤ 0.05.

<sup>w</sup> All values for the different response variables are adjusted means obtained after taking into account the effects of crop load.
Table 3. The effect of five dwarfing rootstocks on increase in tree trunk cross-sectional area and yield of ‘Gibson Golden Delicious’ apple trees. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Increase in TCSA (cm²)</th>
<th>Yield (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>21.9 a²</td>
<td>25.7 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>18.1 a</td>
<td>16.4 b</td>
</tr>
<tr>
<td>G.16</td>
<td>14.5 a</td>
<td>11.8 b</td>
</tr>
<tr>
<td>CG.3041</td>
<td>11.0 a</td>
<td>8.4 b</td>
</tr>
<tr>
<td>B.62-396</td>
<td>15.6 a</td>
<td>9.9 b</td>
</tr>
</tbody>
</table>

² Means followed by the same letter within columns are not significantly different according to PDIF at a P value of ≤ 0.05.
Table 4. The effect of five dwarfing rootstocks on average fruit weight and percentage of fruits greater than 68 mm of ‘Gibson Golden Delicious’ apples at harvest. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Average fruit weight (g)</th>
<th>Fruits &gt; 68 mm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>181 a²</td>
<td>173 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>168 a</td>
<td>157 b</td>
</tr>
<tr>
<td>G.16</td>
<td>172 a</td>
<td>167 ab</td>
</tr>
<tr>
<td>CG.3041</td>
<td>174 a</td>
<td>172 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>192 a</td>
<td>238 a</td>
</tr>
</tbody>
</table>

² Means followed by the same letter within columns are not significantly different according to PDIFF at a P value of ≤ 0.05.

� Estimated crop load levels of 9 and 12 fruits per cm² of TCSA were not achieved for CG.3041 and B.62-396 rootstocks.
Table 5. The effect of five dwarfing rootstocks on starch content and soluble solids content of ‘Gibson Golden Delicious’ apples at harvest. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Starch content</th>
<th>Soluble solids content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm$^2$ of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>2.7 c$^2$</td>
<td>2.8 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>3.1 bc</td>
<td>2.9 a</td>
</tr>
<tr>
<td>G.16</td>
<td>2.6 c</td>
<td>2.8 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>4.3 a</td>
<td>3.1 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>3.2 b</td>
<td>2.8 a</td>
</tr>
</tbody>
</table>

$^2$ Means followed by the same letter within columns are not significantly different according to PDiff at a $P$ value of $\leq 0.05$. 
Table 6. The effect of five dwarfing rootstocks on fruit flesh firmness and hue angle of ‘Gibson Golden Delicious’ apples at harvest.

Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Fruit firmness (N)</th>
<th>Hue angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm$^2$ of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>86.5 a$^z$</td>
<td>92.9 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>84.3 ab</td>
<td>88.8 ab</td>
</tr>
<tr>
<td>G.16</td>
<td>91.1 a</td>
<td>91.2 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>73.1 bc</td>
<td>81.5 b</td>
</tr>
<tr>
<td>B.62-396</td>
<td>71.5 c</td>
<td>80.8 b</td>
</tr>
</tbody>
</table>

$^z$ Means followed by the same letter within columns are not significantly different according to PDIFF at a $P$ value of $≤$ 0.05.
Fig. 1. Effects of rootstocks on fruit growth of ‘Gibson Golden Delicious’ apples as measured by fruit diameter (mm). Values were adjusted for crop load as a covariate. Points are LS means ± standard error for the mean.
CHAPTER 3. INFLUENCE OF CROP LOAD ON TREE GROWTH, YIELD, FRUIT QUALITY ATTRIBUTES, AND RETURN BLOOM OF SCAB-RESISTANT APPLES

A paper to be submitted to the Journal of the American Pomological Society

Dennis N. Katuuramu, Gail R. Nonnecke, Paul A. Domoto, and Lester A. Wilson

ADDITIONAL INDEX WORDS. *Malus ×domestica*, soluble solids, flesh firmness, fruit skin color, hue angle, lightness, yield efficiency, TCSA, *Venturia inaequalis*, Malling 9

Abstract

Growing scab-resistant apple cultivars can allow for reduction in pesticide usage and a decrease in environmental damage. The influence of crop load on tree growth, yield, and fruit quality attributes of ‘Redfree’, ‘Liberty’, and ‘GoldRush’ trees grown on Malling 9 rootstock was investigated at the Iowa State University Horticulture Research Station in an eight-year-old orchard. Tree growth was less with an increasing crop load while yield was positively related to crop load. Average fruit weight and percentage of marketable fruit (greater than 68 mm) were negatively affected by crop load for all cultivars. At higher crop loads, fruits from ‘Redfree’ apples were smaller and more firm. Soluble solids concentration was negatively related to fruit firmness for ‘Redfree’ and ‘GoldRush’ apples. Results showed that a crop load range of 6-8 fruits per cm² of trunk cross-sectional area resulted in the best yield and the highest proportion of marketable fruit that was greater than 68 mm.
Introduction

Apple scab, caused by *Venturia inaequalis* (Cooke.) G. Wint., is a major disease affecting apple (*Malus × domestica* Borkh.) production in the Midwest (Ellis et al., 1998). Apple scab control can require growers in the Midwest to use protectant fungicide sprays, usually 10 to 15 sprays per year (Gadoury et al., 1989). Apple breeding programs have developed over 30 releases of scab-resistant cultivars since 1970 with recent introductions having improved fruit quality and consumer acceptance (Crosby et al., 2002). ‘Redfree’ and ‘GoldRush’ are from a cooperative breeding program involving Purdue University, Rutgers-The State University of New Jersey, and The University of Illinois at Urbana Champaign (Crosby et al., 1994; Williams et al., 1981) while ‘Liberty’ was introduced from the Cornell University breeding program (Lamb et al., 1978). With resistance to apple scab, growers can produce high-quality fruit with fewer fungicide sprays while lowering production costs and protecting the environment.

Crop load management by chemical methods or manual removal of blossoms or fruits has been shown to improve fruit quality in apples (Greene et al., 1990). For the scab-resistant cultivars to be grown at optimal production levels, information on their cropping capacities and the effects of crop load on tree growth and fruit quality attributes is needed. Previous research on scab-resistant cultivars investigated the effects of integrated and organic fruit production systems on fruit maturity and quality of Liberty apples (Peck et al., 2009), and effects of rates and time of application of nitrogen fertilizer on fruit size and market value of GoldRush apples (Wargo et al., 2003). The objective of this research was to determine the relationship between increasing crop load on tree growth, fruit size, fruit quality variables, and return bloom of three scab-resistant cultivars under Iowa conditions.
Materials and Methods

Experimental site and plant materials

The experiment was conducted at the Iowa State University Horticulture Research Station near Ames, IA (lat. 42°10’06”N, long. 93°64’09”W), during the 2011 growing season. The site was part of a seven-year-old orchard trained to a vertical axis system with three scab resistant apple cultivars (Redfree, Liberty, and GoldRush) grown on Malling 9 (M.9) rootstock. The three cultivars served as pollinizers for each other.

The soil was primarily a Nicolette loam (fine loamy, mixed, superactive, mesic Acquic Hapludolls) (USDA, 1984). Standard orchard production practices (trickle irrigation, nutrient supply, and pest and disease management) were uniform across all experimental units (Lewis et al., 2009). Treatments included three scab-resistant apple cultivars and crop load which was manually adjusted to values ranging from 3 to 13 fruits per cm² of trunk cross-sectional area (TCSA). Four crop load levels were estimated at 3, 6, 9, and 12 fruits per cm² of TCSA. A total of 156 trees were used for all three cultivars and included four crop load estimates and ten replications as single-tree replicates. Trunk circumference for each tree was measured 25 cm above the graft union and was used to calculate the trunk cross-sectional area as described by Strong and Azarenko (2000) and Westwood and Roberts (1970).

Fruit and tree growth

Fruit diameter was recorded at weekly intervals on seven randomly tagged fruits from the lower, middle, and upper parts of each tree canopy using a digital hand-caliper (Digimatic, Model 50-321, Mitutoyo, Co., Japan). Fruit diameter measurement began on 21 June [37 days after full bloom (DAFB)] for Redfree, 41 DAFB for Liberty and 40 DAFB for GoldRush apple trees and one measurement was taken for each fruit every week. Tree growth was determined
by computing the difference in trunk cross-sectional area (TCSA) of the spring (19 April) and fall (26 October) measurements during the 2011 growing season.

Yield and fruit quality attribute measurements

Harvest occurred for ‘Redfree’ on 15 August or 91 DAFB, ‘Liberty’ on 27 September (136 DAFB), and ‘GoldRush’ on 20 October (158 DAFB). Fruits from each tree were counted and weighed to obtain total yield. Average fruit weight was obtained by dividing total fruit weight by the number of fruits per tree. The fruits were sized on a rotary Greefa A3 apple sizer (Model 86637, Type 3, Greefa Co., Utrecht, The Netherlands) and counted for seven size categories. The seven fruit size categories included, ≤ 57 mm, 58 mm - ≤ 63 mm, 64mm - ≤ 70 mm, 71 mm - ≤ 76 mm, 77 mm - ≤ 83 mm, 84 mm - ≤ 89 mm, and > 89 mm. The total weight and fruit number per tree were used to compute average fruit weight. Six apples within the average fruit size per tree were randomly selected and evaluated for the fruit quality attributes of starch pattern index, firmness, soluble solids content, and fruit skin color. Starch index values were determined by staining half fruit slices with iodine solution for two minutes and comparing the area of the fruit tissue stained by iodine with standard color charts on a scale of 1 to 9 (1 representing high staining with starch throughout the flesh and 9 less staining with little or no starch in the flesh) as described in Brookfield et al., (1997) and Fan et al., (1995).

Flesh firmness was measured using a Universal Instron Testing Machine (Model 5566, Instron Corporation, Norwood, MA, USA) and was determined as the force in Newtons required to penetrate the fruit tissue to a depth of 7.9 mm using a Magness-Taylor round penetration probe 11.1 mm in diameter at a penetration rate of 24 mm per minute (Abbott et al., 1976). Two penetrations on the opposite sides of each whole, unpeeled fruit
were made at the fruit equator and the values averaged to get the firmness value per fruit. A digital, temperature-compensated refractometer (Atago Co., Tokyo, Japan) was used to determine soluble solids content of the juice extracted from homogenized slices from opposite sides of each fruit using a fruit blender as described by Mitcham and Kader (1996). All fruit quality tests were completed within three days after harvest and during this period fruits were held in 4.54 kg-size drawstring, vented polyethylene bags (Monte Package Co., Riverside, MI) and refrigerated storage at 3.3°C and maintained at 95% relative humidity at the Iowa State University Horticulture Research Station.

Fruit skin color was measured using a bench top Hunter LabScan XE colorimeter (Hunterlab, Reston, VA) using Commission Internatioanle d’Eclairage (CIE) illuminant D65, 10° standard observer, and a port size of 40 mm. The colorimeter was calibrated using black and white tiles and used CIE L*a*b* color space coordinates (where L* value corresponds to a dark-bright scale of 0-100; 0=black and 100=white, a* is negative for green and positive for red; b* is negative for blue and positive for yellow). Chroma was computed using \((a^* + b^*)^{0.5}\) and hue angle was determined as the arc-tan of \((b*/a^*)\) as described by McGuire (1992). For each fruit, color values were measured at both the reddest and the greenest points of the fruit equator. For red-colored cultivars (Redfree and Liberty), the fruits at harvest were visually assessed for background red color using a measuring tape and the values recorded as percentages of the fruit surface exhibiting the red color.

Six ‘GoldRush’ fruits per tree were placed in vented polyethylene bags. All the above fruit quality attributes (fruit skin color, soluble solids content, and firmness) also were conducted on ‘GoldRush’ apple fruits that were held in refrigerated storage for 60 d at 3.3°C and maintained at 95% relative humidity.
Return bloom was determined by counting the number of flower clusters per tree during the 2012 bloom period (4 April).

Statistical analysis

The crop load treatments were assigned in a completely randomized design, and for all the three cultivars crop load was treated as a continuous variable and data were analyzed using analysis of covariance (ANCOVA). Slopes to determine the effects of crop load and estimates of the Least Square means were determined using SAS (Littell et al., 2006; Miliken and Johnson, 2002).

Results

Increasing crop load was associated with a lower increase in trunk cross-sectional area (smaller trees) for ‘Liberty’ and ‘GoldRush’ but not for ‘Redfree’ apple trees (Table 1). Yield (total fruit weight) was positively related with an increase in crop load for each of the three cultivars. Yield efficiency also increased with increasing crop load. Increasing crop load negatively affected average fruit weight and percentage of fruits that were greater than 68 mm in diameter.

Starch index values increased with increasing crop loads for apples from cultivars Redfree and GoldRush indicating a reduction in starch content in the fruit flesh (Table 2). Fruit firmness increased with increasing crop load for the ‘Redfree’ apples but was not affected by crop load for the ‘Liberty’ and ‘GoldRush’ apples. Soluble solids concentration was negatively related to crop load for ‘Redfree’ and ‘GoldRush’ apples, but crop load did not affect soluble solids of apples harvested from ‘Liberty’ trees. Crop load did not affect color variables
(background color, lightness, hue angle, and chroma) of apples from ‘Redfree’ and ‘Liberty’
trees.

Hue angle, lightness, and chroma of ‘GoldRush’ apples at harvest were affected by
crop load and also after 60 d of refrigerated storage (Table 3). After storage, crop load did not
have an effect on fruit firmness but affected soluble solids content.

Fruit growth as measured in terms of fruit diameter was reduced by increases in crop
load (Fig. 1, 2, and 3) and our results showed that crop load increments of 3 fruits per cm$^2$ of
TCSA reduced final fruit size by 2 mm for ‘Liberty’ and ‘GoldRush’ apples and by 3 mm for
‘Redfree’ apples (Table 4).

Increasing crop load in the growing season of 2011 negatively affected return bloom as
measured by number of flower clusters per tree and number of flower clusters per cm$^2$ of
(Table 5).

A plot of both yield and percentage of fruits greater than 68 mm against crop load for
the three cultivars indicated that the optimal crop range for a better yield with a better
percentage of marketable fruit to be 6 to 8 fruits per cm$^2$ of TCSA (Fig. 4, 5, and 6).

**Discussion**

Westwood and Roberts (1970) reported that the correlation between TCSA and the
production potential of a tree is affected by different tree management, pruning regimes, and
crop load. Increasing crop load negatively affected TCSA of the scab-resistant cultivars. The
negative relationship between tree growth and crop load may have been caused by the
competing sinks for assimilates especially assimilates being channeled to the fruits instead of
tree growth and development. ‘Redfree’ apples were harvested during the summer (15 August) and an early harvest date could have allowed the trees greater time to recover from the effects of crop load on tree growth. Yield is a function of factors including flower bud number, fruit number, and fruit size, and an increasing crop load typically increases total fruit weight per tree, as occurred in our study. The reduction in average fruit weight and percentage of marketable fruit (fruit that was greater than 68 mm) at increasing crop load could have been due to competition for assimilates and limited number of leaf area to fruit ratio at high crop loads. The results of this study agree with previous reports that yield declines with reducing crop loads but marketing advantages of larger fruit size are increased (Blanco, 1987; Nielsen and Dennis, 1993; Hull et al., 1995).

As crop load increased, fruit firmness and starch content decreased (starch index value increased) in ‘Redfree’ and ‘GoldRush’ apples while the soluble solids concentration was reduced. An increase in fruit numbers per tree might have resulted in competition for assimilates and delayed fruit maturity. The reduced starch content in the apple flesh at higher crop load levels in conjunction with lower soluble solids observed indicates that assimilates available for fruit growth became limited as the trees had higher crop loads. As a result, less starch was being stored in the fruit during the growing season.

Palmer et al. (1997) documented that heavy crop load produces smaller fruits compared to a lighter crop load while working on ‘Braeburn’ apple trees. Our data confirmed this association between crop load and fruit size. Apples harvested from heavier crop loads were smaller in size and had less sugar content. This could be due to the competing sinks for assimilates resulting in delayed maturation and small-sized fruits as reported by Nielsen and Dennis (1993) in their work on thinning of ‘Delicious’ apples. A crop load range of 6-8 fruits
per cm² of TCSA resulted in optimum yield with the highest percentage of marketable fruit (greater than 68 mm) and this could have been due to adequate availability of assimilates for fruit growth with minimum competition compared to that experienced by apples grown at crop load levels higher than 8 fruits per cm² of trunk cross-sectional area.

After 60 d of refrigerated storage ‘GoldRush’ apples exhibited high firmness values, hue angle (yellower fruit skin color), and an increased amount of soluble solids concentration. Crosby et al., (1994) mentioned that flavor, firmness, and acidity of ‘GoldRush’ can be retained for more than 6 months in regular cold storage and its appearance and eating quality improves during storage. The inverse relationship between crop load and return bloom for all the three apple scab-resistant cultivars could have been due to competition for assimilates at higher crop load levels where the trees allocated more assimilates to fruit growth than floral bud initiation and differentiation for the subsequent growing season. Byers, (1993) reported that removal of fruit (thinning) has the opposite effect of promoting flower initiation for the subsequent growing season. Tromp, (2000) and Meland, (1997) reported that reducing the number of fruits per tree increases the relative amount of leaf area per fruit as well as the availability of carbohydrates for the remaining fruits. Low fruit numbers per tree can improve flower bud induction and return bloom for the subsequent season.

**Conclusion**

This study represents the first evaluation of apple fruit quality characteristics of Redfree, Liberty, and GoldRush scab-resistant cultivars as affected by crop load. A crop load range of 6 to 8 fruits per cm² resulted in a high yield with the highest proportion of marketable fruit (percent fruit greater than 68 mm). Crop load should be managed by apples growers to
optimize the effects of fruit number on average fruit weight, fruit size, and return bloom. Annual cropping of optimal yields with fruit sizes greater than 68 mm increases the profitability and sustainability of apple production.

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799.
Table 1. Relationship between crop load with tree growth and yield variables for ‘Redfree’, ‘Liberty’, and ‘GoldRush’ apples at harvest. Analysis of covariance was used to estimate the least squares means for the four different crop loads.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Variable measured</th>
<th>R² (%)</th>
<th>Slope</th>
<th>P value</th>
<th>Crop load (fruits/cm² of TCSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Redfree</td>
<td>Increase in TCSA (cm²)</td>
<td>2.8</td>
<td>-0.15</td>
<td>0.2375</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Yield (kg)</td>
<td>23.5</td>
<td>1.48</td>
<td>0.0003</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>Yield Efficiency (kg•cm⁻²)</td>
<td>77.2</td>
<td>0.06</td>
<td>0.0001</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Avg. fruit. wgt (g)</td>
<td>65.5</td>
<td>-5.71</td>
<td>0.0001</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Fruits &gt; 68 mm (%)</td>
<td>63.4</td>
<td>-7.11</td>
<td>0.0001</td>
<td>95</td>
</tr>
<tr>
<td>Liberty</td>
<td>Increase in TCSA (cm²)</td>
<td>23.8</td>
<td>-0.54</td>
<td>0.0002</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>Yield (kg)</td>
<td>14.5</td>
<td>1.19</td>
<td>0.0044</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Yield Efficiency (kg•cm⁻²)</td>
<td>80.6</td>
<td>0.09</td>
<td>0.0001</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Avg. fruit. wgt (g)</td>
<td>15.4</td>
<td>-2.91</td>
<td>0.0034</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Fruits &gt; 68 mm (%)</td>
<td>48.1</td>
<td>-2.94</td>
<td>0.0001</td>
<td>44</td>
</tr>
<tr>
<td>GoldRush</td>
<td>Increase in TCSA (cm²)</td>
<td>30.3</td>
<td>-0.39</td>
<td>0.0001</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>Yield (kg)</td>
<td>37.8</td>
<td>2.35</td>
<td>0.0001</td>
<td>22.9</td>
</tr>
</tbody>
</table>
Table 1 continued

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Efficiency (kg•cm⁻²)</td>
<td>88.9</td>
<td>0.09</td>
<td>0.0001</td>
<td>0.49</td>
<td>0.76</td>
<td>1.02</td>
</tr>
<tr>
<td>Avg. fruit. wgt (g)</td>
<td>64.6</td>
<td>-5.63</td>
<td>0.0001</td>
<td>182</td>
<td>165</td>
<td>148</td>
</tr>
<tr>
<td>Fruits &gt; 68 mm (%)</td>
<td>64.5</td>
<td>-5.28</td>
<td>0.0001</td>
<td>89</td>
<td>73</td>
<td>57</td>
</tr>
</tbody>
</table>

*Regression (R²) values indicate how much percentage of the change in the response variable for each cultivar is explained by changes in crop load.*

*Positive slope values indicate that increasing crop load by one unit increases the indicated response variable by that slope value.*

*Negative slope values imply that increasing the crop load by one unit reduces the response variable by the shown slope value.*

*P values greater than 0.05 indicate that the slope for a given variable of a particular cultivar was not significant while p values less than 0.05 denote significant slopes.*
Table 2. Relationship between crop load with fruit quality variables for ‘Redfree’, ‘Liberty’, and ‘GoldRush’ apples at harvest.

Analysis of covariance was used to estimate the least squares means for the four different crop loads.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Variable measured</th>
<th>R²</th>
<th>Slope</th>
<th>P value</th>
<th>Crop load (fruits/cm² of TCSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Redfree</td>
<td>Starch index value</td>
<td>8.0</td>
<td>0.05</td>
<td>0.0443</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Fruit firmness (N)</td>
<td>22.3</td>
<td>1.37</td>
<td>0.0005</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Soluble solids content (%)</td>
<td>31.5</td>
<td>-0.10</td>
<td>0.0001</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Background color (%)</td>
<td>0.05</td>
<td>-0.06</td>
<td>0.8763</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Hue angle (°)</td>
<td>3.6</td>
<td>0.53</td>
<td>0.1812</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Lightness</td>
<td>0.31</td>
<td>-0.16</td>
<td>0.6991</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Chroma</td>
<td>3.7</td>
<td>-0.10</td>
<td>0.1788</td>
<td>38</td>
</tr>
<tr>
<td>Liberty</td>
<td>Starch index value</td>
<td>0.56</td>
<td>-0.01</td>
<td>0.5910</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Fruit firmness (N)</td>
<td>1.6</td>
<td>-0.32</td>
<td>0.3551</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Soluble solids content (%)</td>
<td>5.9</td>
<td>-0.14</td>
<td>0.0766</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>Background color (%)</td>
<td>0.007</td>
<td>0.01</td>
<td>0.9512</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Hue angle (°)</td>
<td>4.6</td>
<td>-0.29</td>
<td>0.1179</td>
<td>27</td>
</tr>
</tbody>
</table>
Table 2 continued

<table>
<thead>
<tr>
<th></th>
<th>Lightness</th>
<th></th>
<th>0.1113</th>
<th>40</th>
<th>40</th>
<th>39</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chroma</td>
<td>4.2</td>
<td>-0.16</td>
<td>0.1361</td>
<td>30</td>
<td>30</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>GoldRush</td>
<td>Starch index value</td>
<td>14.7</td>
<td>0.07</td>
<td>0.0055</td>
<td>3.3</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Fruit firmness (N)</td>
<td>1.4</td>
<td>-0.27</td>
<td>0.4005</td>
<td>133</td>
<td>132</td>
<td>132</td>
<td>131</td>
</tr>
<tr>
<td>Soluble solids content (%)</td>
<td>23.2</td>
<td>-0.26</td>
<td>0.0003</td>
<td>14.4</td>
<td>13.6</td>
<td>12.8</td>
<td>12.1</td>
</tr>
<tr>
<td>Hue angle (°)</td>
<td>22.0</td>
<td>0.51</td>
<td>0.0005</td>
<td>88</td>
<td>89</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>Lightness</td>
<td>9.5</td>
<td>-0.16</td>
<td>0.0282</td>
<td>71</td>
<td>71</td>
<td>71</td>
<td>70</td>
</tr>
<tr>
<td>Chroma</td>
<td>39.7</td>
<td>-0.54</td>
<td>0.0001</td>
<td>51</td>
<td>49</td>
<td>48</td>
<td>46</td>
</tr>
</tbody>
</table>

Regression (R²) values indicate how much percentage of the change in the response variable for each cultivar is explained by changes in crop load.

Positive slope values indicate that increasing crop load by one unit increases the indicated response variable by that slope value. Negative slope values imply that increasing the crop load by one unit reduces the response variable by the shown slope value.

P values greater than 0.05 indicate that the slope for a given variable of a particular cultivar was not significant while p values less than 0.05 denote significant slopes.
Table 3. Relationship between crop load with fruit quality variables for ‘GoldRush’ apples after 60 d of refrigerated storage. Analysis of covariance was used to estimate the least squares means for the four different crop loads.

<table>
<thead>
<tr>
<th>Variable measured</th>
<th>( R^2 ) (%)</th>
<th>Slope</th>
<th>( P ) value</th>
<th>Crop load (fruits/cm(^2) of TCSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soluble solids content (%)</td>
<td>8.0(^z)</td>
<td>-0.09(^y)</td>
<td>0.0447(^x)</td>
<td>14.9 14.7 14.4 14.1</td>
</tr>
<tr>
<td>Fruit firmness (N)</td>
<td>0.42</td>
<td>-0.21</td>
<td>0.6506</td>
<td>114 113 113 112</td>
</tr>
<tr>
<td>Hue angle (°)</td>
<td>14.9</td>
<td>0.36</td>
<td>0.0052</td>
<td>86   87  88  89</td>
</tr>
<tr>
<td>Lightness</td>
<td>8.6</td>
<td>-0.14</td>
<td>0.0363</td>
<td>72   72  71  71</td>
</tr>
<tr>
<td>Chroma</td>
<td>21.1</td>
<td>-0.36</td>
<td>0.0007</td>
<td>54   53  52  51</td>
</tr>
</tbody>
</table>

\(^z\) Regression (\( R^2 \)) values indicate how much percentage of the change in the response variable for each cultivar is explained by changes in crop load.

\(^y\) Positive slope values indicate that increasing crop load by one unit increases the indicated response variable by that slope value.

\(^x\) Negative slope values imply that increasing the crop load by one unit reduces the response variable by the shown slope value.

\(^x\) \( P \) values greater than 0.05 indicate that the slope for a given variable of a particular cultivar was not significant while \( p \) values less than 0.05 denote significant slopes.
Fig. 1. Effect of crop load on fruit growth ‘Redfree’ apples as measured by fruit diameter (mm). Points are least square means estimates ± standard error of the means.
Fig. 2. Effect of crop load on fruit growth ‘Liberty’ apples as measured by fruit diameter (mm).

Points are least square means estimates ± standard error of the means.
Fig. 3. Effect of crop load on fruit growth ‘GoldRush’ apples as measured by fruit diameter (mm). Points are least square means estimates ± standard error of the means.
Fig. 4. Graph for determining optimal crop load for high fruit yield while ensuring highest proportion of marketable fruit greater than 68 mm for ‘Redfree’ apples.
Fig. 5. Graph for determining optimal crop load for high fruit yield while ensuring highest proportion of marketable fruit greater than 68 mm for ‘Liberty’ apples.
Fig. 6. Graph for determining optimal crop load for high fruit yield while ensuring highest proportion of marketable fruit greater than 68 mm for ‘GoldRush’ apples.
CHAPTER 4. GENERAL CONCLUSIONS

For Iowa apple growers to maintain a sustainable fruit production enterprise, an understanding of the influence of new fully dwarfing rootstocks with varying crop loads is needed to determine the potential apple productivity. Information on how to manage new scab-resistant fruiting cultivars regarding optimal crop load and its effects on yield, growth and development, and fruit quality variables is important for adoption of apple cultivars for sustainable production.

This research addressed the aforementioned needs by investigating the influence of dwarfing rootstocks on the yield, fruit quality, and return bloom of ‘Gibson Golden Delicious’ apples. The relationship between crop load and tree growth, yield, fruit quality, and return bloom of scab-resistant cultivars was evaluated in a second study.

Rootstock performance

Malling 26 resulted in a larger increase in tree trunk growth than G.16, CG.3041, and B.62-396. Also, trees grown on M.26 had a higher yield than trees on CG.3041 and B.62-396. The percentage of marketable fruits was smallest for trees grown on G.16 rootstock when compared to M9.T337, CG. 3041, and B.62-396. Return bloom was highest for trees grown on M.26 as compared to CG.3041 and B.62-396.

At harvest, rootstock affected soluble solids content and fruit firmness. Fruits from trees grown on B.62-396 were sweeter than those from trees on G.16 rootstock. Fruits from trees on M.26, M.9T337, and G.16 were more firm than those from CG.3041 and B.62-396. Rootstocks did not affect fruit skin color (hue angle) at harvest and after 60 d or refrigerated storage. Soluble solids content and fruit firmness were not affected by crop load after 60 d of refrigerated storage.
Scab-resistant cultivars

Crop load reduced tree trunk growth in ‘Liberty’ and ‘GoldRush’ apple trees. Crop load reduced the rate of fruit growth and final fruit size. An increment of 3 fruits per cm$^2$ of TCSA among the crop load levels resulted in a reduction in final fruit diameter of 2 mm for ‘Liberty’ and ‘GoldRush’ apples and a reduction of 3 mm for ‘Redfree’ apples. Fruit size (average fruit weight and percent of fruit greater than 68 mm) was associated with changes in crop load with negative slopes for Redfree, Liberty and GoldRush cultivars. Total yield increased with increasing crop load for all the three cultivars. Soluble solids content was reduced at high crop loads for ‘Redfree’ and ‘GoldRush’ apples. Crop load increased the fruit firmness for ‘Redfree’ apples. The amount of return bloom declined with increasing crop load from the previous year. The optimum crop load level for all the three cultivars ranged from 6 – 8 fruits per cm$^2$ of TCSA. Crop load increments of 3 fruits per cm$^2$ of TCSA resulted in a reduction of 2 mm in final fruit diameter for ‘Liberty’ and ‘GoldRush’ apple trees and 3 mm reduction in final fruit diameter for ‘Redfree’ apple trees.

Future research

Multiple years of research on apples as a perennial crop should be completed to ensure consistency of the results. Fruit quality factors in addition to those investigated in this study such as ethylene content pre and post- harvest storage, organic acid content, and sensory attributes such as flavor should be investigated.
APPENDIX TABLES

Appendix Table 1. The effect of five dwarfing rootstocks on yield efficiency and flower clusters of Gibson Golden Delicious apple trees. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Yield efficiency (kg•cm$^2$)</th>
<th>Flower clusters/ cm$^2$ of TCSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm$^2$ of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>0.38 a</td>
<td>0.63 b</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>0.41 a</td>
<td>0.71 a</td>
</tr>
<tr>
<td>G.16</td>
<td>0.30 a</td>
<td>0.76 ab</td>
</tr>
<tr>
<td>CG.3041</td>
<td>0.34 a</td>
<td>0.81 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>0.35 a</td>
<td>0.77 ab</td>
</tr>
</tbody>
</table>

* Means followed by the same letter within columns are not significantly different according to PDIF at a $P$ value of $\leq 0.05$. 
Appendix Table 2. The effect of five dwarfing rootstocks on number of flower clusters (return bloom) of Gibson Golden Delicious apple trees. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Number of flower clusters per tree</th>
<th>Number of flower clusters per cm² of TCSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/cm² of TCSA)</td>
<td>Crop load (fruits/cm² of TCSA)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>412 a²</td>
<td>349 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>290 a</td>
<td>278 a</td>
</tr>
<tr>
<td>G.16</td>
<td>314 a</td>
<td>303 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>261 a</td>
<td>252 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>275 a</td>
<td>229 a</td>
</tr>
</tbody>
</table>

² Means followed by the same letter within columns are not significantly different according to PDIFF at a $P$ value of ≤ 0.05.
### Appendix Table 3. Effects of rootstock on fruit skin color of ‘Gibson Golden Delicious’ apples at harvest and after 60 d of refrigerated storage.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>At harvest</th>
<th></th>
<th>After 60 d of refrigerated storage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lightness</td>
<td>Hue angle (°)</td>
<td>Chroma</td>
<td>Lightness</td>
</tr>
<tr>
<td>M.26</td>
<td>76 ab(^{x})</td>
<td>88 a</td>
<td>48 a</td>
<td>79 ab</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>77 a</td>
<td>85 a</td>
<td>46 b</td>
<td>79 ab</td>
</tr>
<tr>
<td>G.16</td>
<td>78 a</td>
<td>88 a</td>
<td>48 a</td>
<td>80 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>78 a</td>
<td>88 a</td>
<td>51 a</td>
<td>79 ab</td>
</tr>
<tr>
<td>B.62-396</td>
<td>75 b</td>
<td>88 a</td>
<td>49 a</td>
<td>78 b</td>
</tr>
</tbody>
</table>

\(^{x}\) Means followed by the same letter with in columns are not different according to PDIFF at a $P$ value of 0.05.

\(^{y}\) All values for the different response variables are adjusted means obtained after taking into account the effects of crop load.
Appendix Table 4. The effect of five dwarfing rootstocks on soluble solids content and fruit flesh firmness of ‘Gibson Golden Delicious’ apples after 60 d of refrigerated storage. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Soluble solids content (%)</th>
<th>Fruit firmness (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/cm² of TCSA)</td>
<td>Crop load (fruits/cm² of TCSA)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>15.9 a</td>
<td>15.9 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>16.1 a</td>
<td>15.6 a</td>
</tr>
<tr>
<td>G.16</td>
<td>16.2 a</td>
<td>15.7 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>15.9 a</td>
<td>15.5 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>16.7 a</td>
<td>15.9 a</td>
</tr>
</tbody>
</table>

* Means followed by the same letter within columns are not significantly different according to PDIFF at a P value of ≤ 0.05.
Appendix Table 5. The effect of five dwarfing rootstocks on fruit skin lightness of ‘Gibson Golden Delicious’ apples at harvest and after 60 d of refrigerated storage. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Lightness at harvest</th>
<th>Lightness after 60 d of refrigerated storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>77 a</td>
<td>77 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>78 a</td>
<td>76 a</td>
</tr>
<tr>
<td>G.16</td>
<td>77 a</td>
<td>76 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>74 a</td>
<td>76 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>77 a</td>
<td>78 a</td>
</tr>
</tbody>
</table>

Notes:

Means followed by the same letter within columns are not significantly different according to PDIF at a \( P \) value of \( \leq 0.05 \).
Appendix Table 6. The effect of five dwarfing rootstocks on fruit skin hue angle of ‘Gibson Golden Delicious’ apples at harvest and after 60 d of refrigerated storage. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Hue angle (°) at harvest</th>
<th>Hue angle (°) after 60 d of refrigerated storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td>Crop load (fruits/ cm² of TCSA)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>M.26</td>
<td>87 a²</td>
<td>89 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>89 a</td>
<td>88 a</td>
</tr>
<tr>
<td>G.16</td>
<td>83 a</td>
<td>85 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>87 a</td>
<td>88 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>89 a</td>
<td>88 a</td>
</tr>
</tbody>
</table>

² Means followed by the same letter within columns are not significantly different according to PDIF at a $P$ value of $\leq 0.05$. 
Appendix Table 7. The effect of five dwarfing rootstocks on chroma of ‘Gibson Golden Delicious’ apples at harvest and after 60 d of refrigerated storage. Analysis of covariance was used to estimate the least squares means at the four different crop loads.

<table>
<thead>
<tr>
<th>Rootstock</th>
<th>Chroma at harvest</th>
<th></th>
<th>Chroma after 60 d of refrigerated storage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td></td>
<td>Crop load (fruits/ cm² of TCSA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>M.26</td>
<td>50 ab</td>
<td>48 ab</td>
<td>46 a</td>
<td>44 a</td>
</tr>
<tr>
<td>M.9 T337</td>
<td>50 ab</td>
<td>48 ab</td>
<td>46 a</td>
<td>44 a</td>
</tr>
<tr>
<td>G.16</td>
<td>48 b</td>
<td>46 b</td>
<td>44 a</td>
<td>42 a</td>
</tr>
<tr>
<td>CG.3041</td>
<td>52 a</td>
<td>48 ab</td>
<td>44 a</td>
<td>40 a</td>
</tr>
<tr>
<td>B.62-396</td>
<td>52 a</td>
<td>51 a</td>
<td>50 a</td>
<td>48 a</td>
</tr>
</tbody>
</table>

* Means followed by the same letter within columns are not significantly different according to PDIF at a P value of ≤ 0.05.
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