Effects of Root Restriction on Tree Development in Ponkan Mandarin (*Citrus Reticulata* Blanco)

Mebelo Mataa and Shigeto Tominaga

Faculty of Agriculture, Kagoshima University, Korimoto 1-21-24, Kagoshima 890-0065, Japan

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ABSTRACT. The effects of root restriction, induced by root restriction bags, was evaluated on 'Yoshida' Ponkan mandarin (*Citrus reticulata* Blanco). Trees were planted in 0.02-m³ volume root wrap bags (RWBs), which were made from woven polystyrene fiber, or root control bags (RCBs) made from nonwoven UV-stabilized Duon polystyrene fibre with plastic bottoms. A direct soil planted, nonrestricted root treatment (DPC) was included as a control. After 3 years, reductions in height (14% to 29%), canopy volume (66% to 43%), girth (10% to 22%), and leaf area (8% to 12%) were recorded in both of the root restriction treatments. Greater reductions occurred in the RWB treatment. Photosynthesis, transpiration, water potential, and leaf carbohydrate content were not affected by root restriction although soil moisture content was lower in the root restricted treatments. Fruiting efficiency (i.e., number of fruit per unit volume of tree canopy) improved only in the RWB treatment over the control. Total soluble solids and the fruit color index were enhanced by root restriction.

Root growth restriction has been found to reduce root and shoot growth, carbon dioxide assimilation, and stomatal conductivity, (Hameed et al., 1987; Ran et al., 1992; Rieger and Marra, 1994). Also reported was an increase in yield efficiency (g fruit/g total dry mass) (Mandre et al., 1995) and leaf carbohydrate content (Robbins and Parr, 1988; Rieger and Marra, 1994). The physiological basis for these responses is not clear and some of the responses cited are considered to be the consequence of, but not the cause of growth reduction (Mandre, et al., 1995).

Citrus root and shoot growth has been reported to cycle alternately, with root growth usually preceding shoot growth (Bevington and Castle, 1985; Marloth, 1949; Waynick and Walker, 1930). However, sometimes the growth of roots and shoots may overlap (Maust and Williamson, 1994). Sauerback and Johnen (1976) suggested that roots respire more rapidly per unit mass than shoots, thus using a higher proportion of total plant carbohydrates. Ponkan mandarin (*Citrus reticulata* Blanco) is a vigorous species with a pronounced upright growth habit (Hodgson, 1967). The large fruited cultivar Yoshida used in this study has a low fruit productivity potential in comparison with other cultivars. It is thought that excessive vegetative growth during the early fruit set period is responsible for a low rate of fruit growth and a high rate of fruit abscission in Ponkan mandarin (Mataa et al., 1996). Root restriction research in fruit plants has largely involved short term responses of peach (Mandre et al., 1995; Rieger and Marra, 1994). This study was initiated to examine long term vegetative and reproductive growth responses of Ponkan mandarin trees to root restriction induced by root restriction bags of different physical characteristics.

Materials and Methods

One-year-old Ponkan (*Citrus reticulata* Blanco 'Yoshida') trees were planted in March 1993 and spaced 2.5 × 2.0 m. Planting position was offset between rows, thus giving a hexagon formation with a uniform 2.5-m spacing between plants. Trees were planted

in 1) root wrap bags (RWBs), which were made from woven polystyrene fiber (Toray Plastics, Tokyo), 2) root control bags (RCBs) made from nonwoven UV-stabilized duon polystyrene fiber with a plastic bottom (Root Control Inc., Oklahoma City, Okla.), and 3) a control that consisted of direct soil planted trees with no root restriction. Volume of both root restriction containers was 0.02 m³. The planting area was prepared as are commercial orchards in Japan. The root restriction bags with trees were buried, just below the soil level, to a depth of ≈30 cm and the control trees were planted in an identical manner to commercial trees. Routine orchard management practices were conducted in all treatments. Data were collected on tree growth, leaf photosynthetic and transpiration rates, water potential, shoot growth, canopy size, and flowering and fruit set. Nonstructural carbohydrates (i.e., glucose, fructose, sucrose, and starch) were determined during summer (August), autumn (October), at flower induction (January), at budbreak (March), at flowering (May), and during the June fruit drop period (July in this region). Carbohydrates were extracted as described by Mataa and Tominaga (1998) and quantified calorimetrically (Dubois et al., 1956 and Somogyi 1951). Fruit soluble solids and titratable acidity were measured by refractometer and NaOH titration respectively. Fruit color development determined by a Hunter Colorimeter (C-5120; Tokyo Denshoku, Co., Tokyo) and tree volume was calculated as described by Castle (1983). A portable infrared porometer (model KIP-8510 version 2.03; Koito Industries, Tokyo) was used to measure photosynthetic and leaf transpiration rates. Leaf water potential was determined, before sunrise and at midday, using a Plant Moisture Tensiometer (model DIK 7000; Daiki Rika Kogyo, Ltd., Tokyo). Digital soil moisture tensiometers (model DIK-3150; Daiki Rika Kogyo, Ltd., Tokyo), set at a depth of 25 cm were used to determine soil moisture status.

The experimental design consisted of a randomized complete block design with three replications (two trees per replication). Data were subjected to an analysis of variance and mean separation was done according to Duncan's multiple range test using the *p* = 0.05 (Little and Hills, 1978).

Results

EFFECTS OF ROOT RESTRICTION ON TREE GROWTH. Twenty five months following planting (April 1995) there were no significant differences in tree height and girth size between all treatments.

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However, canopy volume of RWB treated trees was significantly smaller compared to the control (DPC) (Fig. 1). Nine months later (end of the third growing season, January, 1996), trees of both root restriction treatments had significantly less canopy volume, tree height, and girth than the DPC trees (Fig. 1). By January 1996 there was a significant difference in shoot length between the RWB treatment and the other treatments while on this date, shoot length did not differ between the RCB and DPC treatments (Fig. 1). The ratio of canopy volume between treatments after 34 months was 1 RWB : RCB 1.5 : DPC 3.1 compared to 1 RWB : 1.7 RCB : 2.2 DPC at 24 months. The ratio data indicate a greater growth rate in control and the least growth rate in the RWB treatment while RCB treated trees had an intermediate growth rate (Fig. 1).

SHOOT DEVELOPMENT AND SOIL WATER RELATIONS. There were no significant differences between treatments in photosynthetic and transpiration rates during the three phenological stages studied (i.e., vegetative growth, August 1995; flowering, May 1996; and the termination of the main fruit abscission period, August 1996) (Table 1). Although the soil water potential of all treatments did not differ at the August 1995 and May 1996 sampling periods, the soil water potential in the root restricted treatments was lower than the control on the August 1996 sampling date. Even though differences in soil moisture between some treatments existed on the August, 1996 sampling date, there were no significant differences in leaf water potential between treatments on any of the other sampling dates (Table 1). Leaf area was reduced, over that of the control, by the RWB root restriction treatment on the August 1995 sampling date. Significant differences in leaf area did not exist between the RCB and RWB treatments in August 1995 and differences did not exist between any of the treatments on any remaining sampling date (Table 1).

EFFECTS ON REPRODUCTIVE GROWTH. There were no significant effects of treatment on flower number, total yield, and percent fruit set 4 years following initiation of the study (Table 2). Fruiting efficiency (number of fruit per unit canopy volume) was highest in the RWB trees (64.1), and significantly greater than the DPC trees (28.0). Initially fruit produced on DPC trees were smaller than those from the root restriction treatments, but as the season progressed this difference was lost (Fig. 2). Total soluble solids and titratable acidity were higher in fruit from the RCB trees compared to the other treatments while fruit color development was enhanced by the root restriction treatments (Table 2).

LEAF NONSTRUCTURAL CARBOHYDRATE CONTENT. Leaf nonstructural carbohydrate level was not influenced by treatments (Fig. 3). Nonstructural carbohydrates followed the normal seasonal trend, i.e., increase in the summer, maximize in the winter, then declined as bud break approached (Fig. 3).

Discussion

Root restriction regardless of the treatment used reduced vegetative growth of mandarin trees. This reduction was most severe in the RWB trees. Three years after planting trees grown in root wrap bags were about one third the height of the DPC trees. Growth reduction was intermediate in the RCB grown trees in comparison to RWB and DPC trees. Plants generally maintain a fixed shoot to root ratio (Wareing, 1970). Therefore when root growth is reduced the shoot is similarly affected. We observed the same relationship in mandarin. No effects of root restriction treatment were recorded on leaf photosynthesis, transpiration and water potential, regardless of whether the trees were fruiting or not.

Except for the increase in fruiting efficiency induced by the RWB treatment over the control (Table 2) and an initial (June only)

increase in fruit diameter (Fig. 2), the effects of root restriction seem to be specific to vegetative growth. All other reproductive parameters studied (flowers/tree and yield) did not differ between all treatments applied as well as the fruiting efficiency of RCB and RWB treated trees (Table 2). In some plants restricting root growth also reduces synthesis of root produced growth promoters such as cytokinins particularly when coupled with a reduction in soil water potential (Munns and Sharp, 1993). This would appear also to be a possibility in mandarin because the soil moisture content in the root restricted treatments was slightly lower than that of the direct planted control (Table 2). Fruit unlike vegetative shoots, are able

Fig. 1. Effects of root restriction and direct planting on (RWB = root wrap bag; RCB = root control bag; DPC = directly planted control treatment) on vegetative growth in Ponkan mandarin (*Citrus reticulata* Blanco 'Yoshida'). Bars represent the standard error of the mean of six plants in each treatment.

Table 1. The effects of root restriction and direct planting on photosynthesis and leaf, soil moisture status in Ponkan mandarin (*Citrus reticulata* Blanco 'Yoshida').

Sampling date ^z	Treatment ^y	Photosynthetic rate, CO ₂ basis (mmol·m ⁻² ·s ⁻²)	Transpiration rate, H ₂ O (mmol·m ⁻² ·s ⁻²)	Leaf water potential(MPa)		Leaf area (cm ²) ^x	Soil water potential (kPa)
				Dawn ^x	Midday		
August 1995	RWB	7.66 a ^w	4.00 a	---	-2.13 a	17.5 a	---
	RCB	7.38 a	3.96 a	---	-2.06 a	18.7 ab	---
	DPC	9.60 a	5.02 a	---	-1.99 a	19.8 b	---
May 1996	RWB	2.61 a	1.70 a	-0.48 a	-1.47 a	---	-11.5 a
	RCB	2.70 a	1.89 a	-0.50 a	-1.50 a	---	-12.0 a
	DPC	2.20 a	1.67 a	-0.47 a	1.10 a	---	-7.9 a
August 1996	RWB	6.36 a	3.75 a	-0.43 a	-1.95 a	15.7 a	-10.2 b
	RCB	5.72 a	3.22 a	-0.46 a	-1.92 a	16.8 a	-11.0 b
	DPC	6.38 a	4.02 a	-0.42 a	-1.94 a	17.1 a	-5.2 a

^zDenoting the three phenological stages of complete vegetative (August 1995), flowering (May 1996), and the end of main fruit abscission period (August 1996).

^yIndicates type of bag used to restrict root growth: RWB = root wrap bags, made entirely from woven polystyrene fiber; RCB = root control bags, made from unweaved polystyrene fibre with a plastic bottom; and DPC = the direct planting control, which was typical soil planting without root restriction.

^xInitially only midday leaf water potentials were determined and therefore no data are indicated for August 1995. No data are shown for May 1996 leaf area because the new leaves were still tender and expanding.

^wValues followed by the same letter are not different at $p = 0.05$ according to Duncan's multiple range test.

Table 2. Effects of root restriction and direct planting on reproductive growth in Ponkan mandarin (*Citrus reticulata* Blanco 'Yoshida') at 4 years (1996).

Treatment ^z	Flowers per tree	Total yield ^y	Fruit set (%)	Fruit/m ³ canopy (fruiting efficiency)	Fruit size (cm)	Soluble solids concn (%)	Titratable acidity (%)	Color index ^x	Color difference meter reading		
									L*	a*	b*
RWB	508.8 a ^w	27.7 a	5.8 a	64.1 b	6.8 a	10.5 b	0.94 a	8.1 b	51.4 ab	31.1 a	27.7 a
RCB	867.4 a	39.4 a	5.0 a	50.3 ab	6.8 a	11.8 c	1.14 b	8.3 b	53.1 b	29.5 a	28.8 b
DPC	449.5 a	39.5 a	9.5 a	28.0 a	6.8 a	9.9 a	0.89 a	7.2 a	50.8 a	30.9 a	27.5 a

^zIndicates type of bag used to restrict root growth: RWB = root wrap bags, made entirely from woven polystyrene fiber; RCB = root control bags, made from unweaved polystyrene fibre with a plastic bottom; and DPC = the direct planting control, which was typical soil planting without root restriction.

^yNumber of fruit harvested per tree.

^xRanked visually from 0 (full green) to 10 (full orange) color.

^wValues followed by the same letter are not different at $p = 0.05$ according to Duncan's multiple range test.

to synthesize most of the required growth factors (Coolbaugh, 1983; Hoad, 1978; Talon et al., 1992) and consequently may not experience growth inhibition effects even if there is a reduction in the root supplied component. In our study the most notable reproductive growth effect induced by root restriction was, fruit quality enhancement. The greatest fruit soluble solids concentration was recorded in fruit from the RCB treatment followed by those grown in RWB plots. Fruit from the control treatment had the lowest soluble solids concentration of any fruit produced. Titratable acidity was greatest in fruit from the RCB treatment and fruit color was greatest in the root restricted treatments. This could be partly due to the slightly drier soil conditions in which the root restricted treatments grew since similar effects on fruit quality have been reported to have been induced by withholding water (Yakushiji et al., 1996).

During the early fruit growth stage, fruit on root restricted trees grew at a higher rate than did fruit on the control trees, possibly because of a reduction in shoot-fruit competition (Mataa et al., 1996). The increase in fruiting efficiency (number of fruit per unit of canopy volume) of trees in the RWB treatment over those of the control could have been due to the lower growth rate recorded for RWB treatment. Less tree growth results in enhanced light penetration into the canopy, thus greater fruiting efficiency. Mandre et al., (1995) reported a similar yield efficiency improvement for

Fig. 2. Effects of root restriction (RWB = root wrap bag; RCB = root control bag; DPC = directly planted control treatment) on fruit growth as denoted by fruit diameter, in ponkan mandarin (*Citrus reticulata* Blanco 'Yoshida') in 1996. Bars represent the standard error of the mean of six plants in each treatment.

Fig. 3. Effects of root restriction (RWB = root wrap bag; RCB = root control bag; DPC = directly planted control treatment) on leaf carbohydrate content in Ponkan mandarin (*Citrus reticulata* Blanco 'Yoshida') trees during 1995 and 1996. Bars represent the standard error of the mean of six plants in each treatment.

peach grown under root restriction treatments. Slight differences, due to root restriction have been reported for carbon partitioning among different organs (Rieger and Marra, 1994) and carbon dioxide assimilation (Robbins and Parr, 1988). Reasons advanced for a lack of these responses include differences in species and experimental duration (Mandre et al., 1995). It has been demonstrated that increasing fruit load affects leaf photosynthetic rate (Monselise and Lenz, 1980), leaf carbohydrate content (Hansen, 1967), and fruit size (Fischler et al., 1983). In this study, root restriction did not affect these parameters. Possibly this lack of response was due to a simultaneous reduction in both root system (sink) and the canopy (source) size, resulting in no change in the net sink source equilibrium. Since the effects of root restriction are gradually imposed, it is possible that plants with root restrictions are able to readjust their sink-source equilibria with time so that no net differences are discernible in photosynthetic rate, leaf carbohydrate content, or final fruit size relative to the DPC plants. Also, the photosynthetic rate of Ponkan mandarin is considered to be low, i.e., 70% of that of the common Satsuma mandarin (*Citrus unshiu* Marco.), (Morinaga and Ikeda, 1990). This factor could contribute to the apparent lack of photosynthetic and carbohydrate response of Ponkan mandarin to root restrictions. More in-depth studies on

photosynthesis in Ponkan mandarin, particularly at the whole canopy level, would be needed to answer the questions raised.

It is interesting to note that although the volume of the two restriction bags was the same, different plant responses were observed. The different textures, of the bags could have presented different barriers to root development and fluid exchange rates in the soil and therefore affected plant development differently. Root control bags may be more useful for producing container grown trees because they induce a moderate growth restriction and have a better flower and fruit production balance. Such bags have potential use in high density orchards. Growth reduction by use of containers offers an advantage over the use of dwarfing rootstocks because growth control occurs without compromising fruit quality or rootstock/scion attributes like pest and disease resistance.

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