

Performance of Three Apple Cultivars with 23 Dwarfing Rootstocks During 8 Seasons in Washington¹

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Abstract

The performance of 23 apple rootstocks was evaluated with cultivars Golden Delicious, Granny Smith and Delicious during eight seasons. Rootstocks in the trial, listed in order of increasing tree vigor when measured as trunk cross-sectional area (TCA), were M.27 EMLA, P.16, Mark, V.3, MAC.9, P.22, B.146, M.9, CG.10, P.2, M.9 EMLA, V.1, B.9, O.3, MAC.39, M.26 EMLA, V.7, C6, V.2, M.7A, OAR.1, V.4 and P.1. There was little change in ranking of rootstocks for TCA after year 3 and the ranking of rootstocks was essentially similar with each cultivar. Root suckers were most numerous with MAC.9, V.4, B.146, Mark, P.1 and M.7A. The most precocious rootstocks, based on second year bloom and third year production, were M.9 EMLA, O.3, V.7, B.9, V.1, MAC.9 and M.9, and the least precocious rootstocks were OAR.1, M.7A, P.1, V.4, CG.10, B.146 and M.26 EMLA. With each cultivar, cumulative yield/tree to year 8 increased as rootstock vigor increased. Cumulative yield efficiency (kg yield/cm² TCA) at year 8 was generally highest for the most dwarfing rootstocks (V.3, P.16, B.9, P.22, M.9, MAC.9, B.146, M.9 EMLA, P.2, Mark, O.3 and V.1) and lowest for the most vigorous rootstocks (OAR.1, P.1, V.4, M.7A and C6). There was little change in the ranking of rootstocks for cumulative yield efficiency from year 6 onward and the ranking of rootstocks was generally similar with each cultivar. With ten rootstocks (B.9, O.3, M.26 EMLA, V.7, P.22, V.1, P.2, V.3, MAC.39 and M.9) mean fruit weight adjusted for crop load was not different from M.9 EMLA during six seasons with three cultivars. Rootstocks with the lowest fruit weight were Mark, M.27 EMLA, MAC.9, P.1 and OAR.1. Biennial bearing of Golden Delicious and Granny Smith was more pronounced with vigorous than with dwarfing rootstocks. With Delicious biennial bearing was generally greatest with the more dwarfing rootstocks.

Rootstocks play a key role in the design and management of apple orchards, particularly intensive orchard systems (5). Success with high density orchards of standard growth habit cul-

tivars on soils of medium to strong vigor can be expected only when dwarfing rootstocks are used. By controlling tree size, apple rootstocks directly influence tree density, the requirement for a support system, labor efficiency and the ease of targeting chemical sprays. In addition, rootstocks influence cropping, not only the level of production of mature trees but also precocity and cropping efficiency. Adaptation to the site through resistance to disease and insects, tolerance to edaphic factors, to drought and to extreme temperatures can influence the selection of rootstock (17).

The principal size-controlling clonal apple rootstocks used throughout the world were either gathered together and classified at the East Malling Research Station, England, the original Malling (M.) series, or bred at East Malling and Long Ashton Research Stations from the original Malling rootstocks (MM. series) (17). However, in many fruit districts, these English rootstocks have not adapted well to climate and edaphic factors or to pest and disease pressures. Plant breeders around the world have selected new rootstocks which overcome many of the deficiencies of earlier rootstocks (9, 10, 15, 17, 33, 34, 37). The evaluation of new dwarfing rootstocks is underway in Europe (34, 35) and in North America as part of the NC-140 rootstock evaluation project (5, 22, 23). This study evaluates 1) the performance of 23 rootstocks during eight years, 2) the influence of rootstock on the performance of three cultivars and

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3) the number of years required to accurately assess rootstock influence on tree growth and productivity.

Materials and Methods

An apple rootstock trial was established in May 1986 on a sandy loam soil (Birchmount series) at the Tree Fruit Research and Extension Center, Wenatchee, Washington. The site had been in apple production for over 50 years, resulting in the presence of apple replant disease and lead arsenate soil contamination. An old apple orchard was removed from the site the previous fall. Tree growth at this site, which is adjacent to earlier NC-140 plantings, has been relatively weak in comparison with other North American sites (22, 24, 26). Trees of Smoothee Golden Delicious (GD), Granny Smith (GS) and Redchief Delicious (Campbell strain) (RD) were prepared on the following 23 clonal rootstocks: Budagovsky 9 (B.9), Budagovsky 146 (B.146), C6, Cornell-Geneva 10 (CG.10), Mark, Malling 7A (M.7A), Malling 9 (M.9), Malling 9 EMLA (M.9 EMLA), Malling 26 EMLA (M.26 EMLA), Malling 27 EMLA (M.27 EMLA), Michigan Apple Clone 9 (MAC.9), Michigan Apple Clone 39 (MAC.39), Oregon Apple Rootstock 1 (OAR.1), Ottawa 3 (O.3), P.1, P.2, P.16, P.22, Vineland 1 (V.1), Vineland 2 (V.2), Vineland 3 (V.3), Vineland 4 (V.4) and Vineland 7 (V.7). Mark and M.9 EMLA are virus-free clones (based on current virus detection methods) of MAC.9 and M.9, respectively. All trees were grown at a single nursery.

The experimental design was a split-plot with cultivar as the main plot and rootstock as subplots with 10 individual tree replications for each cultivar/rootstock combination arranged in a randomized complete block design. Cultivar/rootstock combinations with fewer than five surviving trees were not included in the analysis. Although the experimental design allowed for the separation of main effect means (for

rootstock or for cultivar), significant rootstock x cultivar interactions occurred for almost all traits. Therefore, rootstock data are presented as within-cultivar means.

Trees were spaced 1.8 m x 4.9 m, a density of 1134 trees/hectare (6' x 16' 454 trees/acre). All trees were supported with individual poles and trained to a spindle bush system (up to 2.5 m tall with spread less confined than with the slender spindle system). At this spacing with GD and GS, in-row crowding developed in years 7 and 8 with the most vigorous rootstocks P.1, V.4, OAR.1 and M.7A. With these rootstocks, some within-row overlap (.5 m) of canopies was permitted and some within-row containment pruning was required to reduce crowding. The extent of growth into the alleyway was not restricted by pruning and therefore tree growth into the alleyway reflected the vigor of the rootstocks. Crowding therefore may have slightly reduced cropping and tree size (TCA) below their potential with the most vigorous rootstocks. The trial received regular irrigation from a solid set under-tree system. The driveways were grass sod and the trees were in the center of a 1.5 m wide herbicide strip. Insect and disease control and fertilizer applications were based on local recommendations (Crop Protection Guide for Tree Fruits in Washington, EB0419). Both chemical and hand thinning were used to encourage annual cropping and adequate fruit size.

The following characteristics were measured annually: trunk circumference (at 20 cm above bud union), yield/tree (kg), number of fruit/tree and number of root suckers/tree (years 4, 5 and 6 only). Using these data, the following traits were calculated: trunk cross-sectional area (cm²; TCA), mean fruit weight (kg/tree ÷ fruit number/tree), yield efficiency (kg fruit/cm² TCA) and crop load (number of fruit/tree ÷ cm² TCA). Mean fruit weight was adjusted for the covariant crop

load. Biennial bearing index was calculated according to Hoblyn et al. (19). TCA ratio, TCA increase from years 5 to 8 ÷ TCA increase from years 2 to 4, was calculated to determine the relative growth rate of rootstocks during the early versus the later years of the trial.

The frequency of gall-like soil-line swelling (25) of the rootstock was recorded with GD, GS and RD for M.9, M.9 EMLA, MAC.9 and Mark. Trees were evaluated only if the scion/rootstock union was sufficiently above the soil line to avoid confusion of union swelling, typical swelling of the scion at the union with dwarfing rootstocks, with soil-line swelling of the rootstock.

Random samples of 20 mid-shoot leaves from each tree of three cultivars on M.9 EMLA and for each tree on MAC.9 and Mark rootstocks exhibiting soil-line swelling were collected on September 1, 1993, and combined in a bulk sample for each of the 9 cultivar/rootstock combinations. A random 20-leaf subsample of each cultivar/rootstock combination was used for leaf color measurements of 'a', 'b', 'L' and hue (Minolta CR-300 Chroma Meter). The bulk samples were dried and ground for leaf mineral analysis (Soil and Plant Analysis Laboratory, University of Wisconsin-Madison).

Results and Discussion

Tree mortality. Tree survival was generally high except for P.22, V.7 and

Table 1. The incidence of tree death during seven seasons for trees of three apple cultivars with 23 rootstocks.

Rootstock ²	% mortality			3-cultivar total	
	Golden Delicious	Granny Smith	Delicious	No. of trees	% mortality
M.27 EMLA	0	0	12	24	4
P.16	20	0	20	35	11
Mark	0	0	0	30	0
V.3	9	10	10	31	10
MAC.9	0	10	10	30	7
P.22	0	0	60	32	19
B.146	0	12	20	23	13
M.9	0	0	10	30	3
CG.10	0	7	0	38	3
P.2	0	38	40	28	25
M.9 EMLA	0	17	10	32	9
V.1	0	6	0	35	3
B.9	0	40	20	30	20
O.3	0	--	10	20	5
MAC.39	0	0	10	30	3
M.26 EMLA	0	0	0	28	0
V.7	0	0	60	32	19
C.6	0	20	10	30	10
V.2	0	0	0	32	0
M.7A	0	0	20	30	7
OAR.1	8	10	8	34	9
V.4	0	0	0	30	0
P.1	0	10	0	31	3
<hr/>					
No. of trees	234	228	233	695	--
<hr/>					
% mortality:					
Year of planting	0	6	8	--	5
Total to year 7	2	8	14	--	8

²Rootstocks listed in order of increasing tree size (see Table 3).

Table 2. Leaf aluminum, manganese and zinc levels for trees on M.9 EMLA, MAC.9 and Mark rootstocks.

Rootstock	Aluminum (ppm)	Manganese (ppm)	Zinc (ppm)
Mark	247a ^c	85.0a	51.9a
MAC.9	240a	64.1ab	38.5ab
M.9 EMLA	220b	51.6b	27.7b

^cMeans of 3 cultivars; means within columns with the same letter are not significantly different (LSD, P = .05).

P.2 with RD and P.2 and B.9 with GS (Table 1). Of the 25 trees that died with these cultivar/rootstock combinations, 18 died in the year of planting, in part due to late planting and very warm temperatures at planting time.

Five percent of all trees in the trial died the year of planting and by year 7 mortality reached 8%. The cause of tree death after year 1 was not determined. Neither unusually cold temperatures nor fire blight (*Erwinia amylovora*) infection appeared to contribute to tree death. Sparse root systems at planting with trees on P.2 and P.22 may have contributed to their poor transplant survival. Poor survival with these rootstocks was also reported in rootstock trials at 30 sites (22).

Soil-line swelling. Gall-like swelling surrounding the rootstock shank at and below the soil line was observed with two rootstocks, MAC.9 and Mark.

Table 3. Tree size, measured as trunk cross-sectional area (TCA), in the eighth year and the ratio of TCA increase in the late years (5 to 8) to TCA increase in the early years (2 to 4) for 23 apple rootstocks with three scion cultivars.

Rootstock	Trunk cross-sectional area year 8				TCA ratio: increase years 5 to 8 ÷ years 2 to 4		
	Golden Delicious (cm ²)	Granny Smith (cm ²)	Delicious (cm ²)	Mean (% of M.9 EMLA) ^z	Golden Delicious	Granny Smith	Delicious
M.27 EMLA	20.7	13.0	7.4	35	2.7	2.8	1.5
P.16	20.8	20.9	9.3	44	2.4	2.9	1.8
Mark	20.9	30.8	12.4	56	1.3	2.1	1.5
V.3	29.6	17.9	16.9	60	2.2	3.0	2.5
MAC.9	21.2	34.1	13.4	60	1.2	2.1	1.1
P.22	30.4	24.8	--	60•	2.6	2.9	--
B.146	--	32.5	14.6	68•	--	2.9	2.0
M.9	37.2	32.5	14.4	72	3.1	3.2	2.7
CG.10	37.9	39.4	14.9	79	2.8	2.7	2.4
P.2	34.5	34.7	19.2	79	1.9	2.5	2.1
M.9 EMLA	45.5	45.9	22.4	100	2.2	2.5	2.5
V.1	44.6	52.4	26.0	109	3.1	2.3	1.9
B.9	54.1	48.4	30.0	119	2.6	3.3	2.2
O.3	62.8	--	30.5	138•	2.4	--	2.3
MAC.39	52.2	58.5	38.7	138	3.4	3.5	2.4
M.26 EMLA	73.4	51.4	40.7	152	2.4	2.6	2.7
V.7	79.5	82.6	--	178•	2.8	3.1	--
C6	74.9	111.4	31.0	182	2.2	3.5	2.8
V.2	75.1	106.4	40.3	192	2.3	3.2	2.2
M.7A	93.9	--	43.2	200•	2.2	--	2.1
OAR.1	103.1	111.6	55.3	239	2.3	3.3	2.1
V.4	118.7	137.0	58.6	275	2.3	2.8	1.9
P.1	101.9	144.1	65.5	277	2.4	4.0	2.1
LSD P = .05	11.3	18.8	8.3	--	.6	1.0	.7
Cultivar mean ^y	53.7	60.6	28.7	--	2.4	2.9	2.1

^zA % of M.9 EMLA TCA was calculated for each cultivar/rootstock combination and the mean of the three cultivars is listed for each rootstock. These values were used to establish the overall ranking of the 23 rootstocks for their influence on tree size. Means followed by a mark (•) include only two cultivars.

^yMeans of 18 rootstocks common to all 3 cultivars.

Table 4. Correlation among cultivars for trunk cross-sectional area, cumulative yield/tree and cumulative yield efficiency at the end of years 4, 6 and 8.

Year	Correlation coefficient ^z		
	Golden Delicious with Granny Smith	Golden Delicious with Delicious	Granny Smith with Delicious
Trunk cross-sectional area (cm ²)			
4	.951**	.923**	.913**
6	.947**	.917**	.905**
8	.940**	.955**	.910**
Cumulative yield per tree (kg)			
4	.469°	.883**	.544°
6	.570**	.884**	.522°
8	.717**	.909**	.591**
Cumulative yield efficiency (kg/cm ²)			
4	.694**	.544°	.572°
6	.813**	.439 ^{NS}	.469°
8	.863**	.686**	.699**

^z** significant, P = .01; ° significant, P = .05, ^{NS} not significant; n = 19 to 21 rootstocks.

At age 6, 100 percent of trees on MAC.9 (27 of 27) and 90 percent of trees on Mark (9 of 10) but none of the trees on M.9 EMLA (0 of 25) or M.9 (0 of 26) exhibited the soil-line swelling condition. Soil-line swelling was reported with almost all MAC.9 trees but not with other rootstocks in a trial at 7 sites throughout the U.S. (25). The frequency and general appearance of soil-line swelling were similar for MAC.9 and Mark and for trees of the three scion cultivars. Trees on Mark and MAC.9 had lighter green and more yellowish foliage than trees on M.9 EMLA and M.9. Objective mea-

surements of leaf color characteristics 'a,' 'b,' 'L,' and, 'hue' confirmed the visual leaf color observations (data not shown).

Leaf mineral analysis of three cultivars with M.9 EMLA, MAC.9 and Mark rootstocks showed no difference among rootstocks in levels of N, P, K, Ca, Mg, S, B, and Cu (data not shown). Only relatively small differences between rootstocks in foliar mineral content have been reported (1, 30). However, in the present study Al, Mn and Zn leaf levels were higher with Mark than with M.9 EMLA and levels for MAC.9 were intermediate (Table 2). Delicious trees on MAC.9 showed higher Mn content than trees on M.9 EMLA in Arkansas but not in Massachusetts and higher levels of Zn in 2 of 4 seasons in Massachusetts (30).

Root suckers. Suckering was rare with most rootstocks (M.27 EMLA, P.16, V.3, P.22, M.9, CG.10, P.2, M.9 EMLA, V.1, B.9, MAC.39, M.26 EMLA, C6 and OAR.1) (data not shown) which agrees with an earlier report (22). However, the number of suckers was highest with MAC.9, V.4, B.146, P.1, and M.7A and intermediate with Mark, V.2, C6 and O.3. A large number of root suckers has been reported for P.1 and M.7 (22, 23). P.16 and P.22 had very few root suckers in the present study but produced numerous suckers in European trials (33, 35). Early reports indicated that MAC.9/Mark had few suckers (7, 8, 17, 21, 23). However, with these rootstocks in the present study, numerous suckers originated just below the soil line at the periphery of the soil-line swelling.

Table 5. Coefficients of determination (%) with three apple cultivars for the relationship of TCA at planting and at the end of years 1 to 7 with TCA at the end of year 8.

Cultivar	No. of rootstocks	Planting	Coefficients of determination (%) for the relationship of TCA in year 8 with TCA at:						
			the end of years						
			1	2	3	4	5	6	7
Golden Delicious	22	46	65	80	91	96	97	98	99
Granny Smith	21	43	63	79	91	94	97	98	99
Delicious	21	23	39	76	95	98	98	99	99

Tree size. The most dwarfing rootstocks, based on TCA measurements, were M.27 EMLA, P16, Mark, V.3, MAC.9 and P22 (Table 3). The most vigorous rootstocks were V.7, C6, V.2, M.7A, OAR.1, V.4 and P.1. Trees on the standard rootstocks M.26 EMLA and M.7A were approximately 1.5 and 2 times larger than trees on the dwarfing standard M.9 EMLA, respectively. Similar relative tree sizes have been observed in earlier trials with these three rootstocks (13, 23, 28). With each cultivar, trees on virus-free M.9 EMLA were not significantly larger than trees on M.9 (not virus free). However, when TCA (as % of M.9

EMLA) was averaged for the three cultivars, M.9 EMLA trees were 28% larger than M.9 trees. MAC.9 and its virus-free clone Mark did not differ in TCA. Virus-free clones are generally more vigorous than clones with latent viruses (6).

With 14 rootstocks common to the present three-cultivar study and to two multi-site studies with Starkspur Supreme Delicious (M.27 EMLA, P16, MAC.9, P22, M.9, P.2, M.9 EMLA, B.9, O.3, MAC.39, M.26 EMLA, C6, OAR.1 and P.1) the ranking of rootstocks for TCA was essentially similar (22, 23). This study confirms European reports that B.9 tree size is between M.9 EMLA and M.26 EMLA (11, 12, 32, 35). O.3 was also between M.9 EMLA and M.26 EMLA in tree size in the present study and in North American and European trials (4, 18, 20, 23, 35).

P.1 produced trees similar in size to M.7A with GD in this study and in other North American trials (22). With RD, trees on P.1 were larger than trees on M.7A. In contrast, European reports placed P.1 closer to M.9 or M.26 in tree size (11, 12, 35, 37). P.1 in North American and European trials may not be the same clone.

The present study and a companion study in Ohio planted at the same time were the first to evaluate the Vineland rootstocks (15). In both studies V.3 was very dwarfing and produced trees less vigorous than M.9 EMLA. Trees with V.1 were in the M.9 EMLA size range. Trees with V.2 and V.7 were in the M.26 EMLA to M.7 size range, and V.4 trees were similar to or larger than M.7.

Tree size (TCA) at year 8 with Mark and MAC.9 was substantially smaller than with M.9 EMLA in the present study (56 and 60% of M.9 EMLA, respectively). MAC.9 trees were 68% of M.9 EMLA tree size at the end of a 10-year, 27-site NC-140 trial (23) but in the same trial at 5 years MAC.9 and M.9 EMLA trees had similar TCA

Table 6. The influence of rootstock on flowering in the second year for three cultivars.

Rootstock ^y	No. flower cluster/tree ^z		
	Golden Delicious	Granny Smith	Delicious
M.27 EMLA	15.3 (3)	6.7 (8)	3.5 (13)
P.16	6.6 (11)	4.4 (11)	2.4 (15)
Mark	11.4 (6)	6.3 (9)	2.2 (16)
V.3	5.5 (12)	4.0 (12)	6.7 (8)
MAC.9	9.0 (7)	7.7 (5)	3.8 (12)
P.22	9.7	7.4	--
B.146	1.6 (17)	7.4 (6)	2.7 (14)
M.9	6.7 (10)	9.0 (4)	8.4 (6)
CG.10	4.1 (14)	0.5 (17)	6.3 (9)
P.2	14.5 (4)	2.6 (14)	4.0 (11)
M.9 EMLA	21.7 (2)	3.4 (13)	18.0 (3)
V.1	12.9 (5)	6.8 (7)	19.4 (2)
B.9	27.2 (1)	12.0 (2)	17.4 (4)
O.3	23.8	--	8.9
MAC.39	4.4 (13)	0.1 (18)	5.4 (10)
M.26 EMLA	3.6 (15)	9.3 (3)	0.9 (17)
V.7	27.4	6.9	--
C6	7.4 (8)	4.9 (10)	9.6 (5)
V.2	7.2 (9)	1.4 (16)	24.7 (1)
M.7A	0.1	--	2.2
OAR.1	0.0 (18.5)	0.0 (19)	0.0 (19)
V.4	0.0 (18.5)	2.4 (15)	6.8 (7)
P.1	3.4 (16)	13.1 (1)	0.2 (18)
LSD P = .05	13.2	9.4	9.3
Cultivar mean ^x	8.6	5.4	7.5

^zRanks are included in brackets for 19 rootstocks common to all cultivars.

^yRootstocks listed in order of increasing tree size (TCA).

^xMeans of 19 rootstocks common to all 3 cultivars.

Table 7. Influence of rootstock on yield efficiency in year 3 and on cumulative yield efficiency to year 8 for three scion cultivars.

Rootstock ^y	Yield efficiency year 3 (kg/cm ²) ^z			Cumulative yield efficiency to year 8 (kg/cm ²) ^z		
	Golden Delicious	Granny Smith	Delicious	Golden Delicious	Granny Smith	Delicious
M.27 EMLA	.75 (12)	.52 (7)	.70 (10)	2.34 (9)	2.17 (7)	2.09 (11)
P.16	.87 (7)	.68 (5)	.80 (4)	3.31 (3)	2.86 (1)	2.31 (5)
Mark	.88 (6)	.81 (2)	.77 (5)	3.48 (2)	2.53 (4)	2.08 (13)
V.3	.85 (9)	.47 (11)	.93 (3)	3.76 (1)	2.33 (6)	2.65 (2)
MAC.9	.97 (5)	.80 (3)	.76 (7)	3.16 (4)	2.79 (2)	2.15 (10)
P.22	.73	.74	--	2.96	2.54	--
B.146	.53 (16)	.29 (13)	.56 (14)	--	2.13	2.57
M.9	.77 (11)	.85 (1)	.77 (6)	2.61 (8)	2.68 (3)	2.33 (4)
CG.10	.73 (13)	.30 (12)	.61 (13)	2.28 (10)	1.79 (11)	2.08 (12)
P.2	1.03 (2)	.53 (6)	.62 (12)	3.55	1.87	--
M.9 EMLA	.99 (3)	.70 (4)	1.08 (1)	2.67 (6)	2.10 (8)	2.53 (3)
V.1	.97 (4)	.52 (8)	.96 (2)	2.67 (7)	2.08 (9)	2.27 (7)
B.9	.85	--	.66	2.93 (5)	2.44 (5)	2.76 (1)
O.3	.97	--	.70	2.07	--	2.67
MAC.39	1.06 (1)	.15 (16)	.72 (8)	2.24 (11)	1.39 (12)	2.24 (8)
M.26 EMLA	.63 (14)	.50 (9)	.47 (15)	2.04 (12)	1.99 (10)	2.15 (9)
V.7	1.48	.65	--	2.00	1.66	--
C6	.80 (10)	.28 (14)	.68 (11)	1.55 (14)	.81 (14)	2.05 (14)
V.2	.86 (8)	.47 (10)	.72 (9)	1.97 (13)	1.17 (13)	2.30 (6)
M.7A	.49	--	.38	1.31	--	1.99
OAR.1	.12 (18)	.01 (18)	.26 (17)	.88 (17)	.38 (17)	1.13 (17)
V.4	.59 (15)	.13 (17)	.27 (16)	1.37 (15)	.68 (15)	1.87 (15)
P.1	.39 (17)	.17 (15)	.09 (18)	1.23 (16)	.63 (16)	1.29 (16)
LSD P = .05	.24	.34	.24	.51	.60	.51
Cultivar mean ^x	.77	.45	.65	2.38	1.81	2.13

^zRanks are included in brackets for rootstocks common to all cultivars.

^yRootstocks listed in order of increasing tree size (TCA).

^xMeans of 17 rootstocks (18 for year 3 yield efficiency) common to all 3 cultivars.

(21). Mark was originally described as similar to M.26 or between M.9 and M.26 in tree size (7, 8).

To evaluate the relative growth of trees during the early years of the trial versus growth in the later years, a ratio was calculated of the increase in TCA in years 5 through 8 divided by the increase in years 2 through 4. This ratio showed that with most rootstocks the increase in tree growth during the later period was two to three times the increase in the earlier period, e.g., with M.9 EMLA the ratios were 2.2, 2.5 and 2.5 for GD, GS and RD, respectively (Table 3). With MAC.9 and Mark ratios were less than for M.9 EMLA with GD and RD, indicating

that trees on these rootstocks had slowed in their growth during the later years in comparison with M.9 EMLA and other rootstocks. With GS the smallest ratios, although not significantly smaller than for M.9 EMLA, also occurred with MAC.9 and Mark. In a 14-year-old trial in Massachusetts, the relative growth rate of Starkspur Supreme Delicious trees with MAC.9 also slowed in relation to other rootstocks after year 5 (4).

The influence of rootstock on relative tree size in years 4, 6 and 8 was similar for cultivars with a standard growth habit (GD), a tip-bearing fruiting habit (GS) or a spur-type growth and fruiting habit (RD) (Table 4). Worldwide root-

Table 8. The influence of rootstock on cumulative yield/tree (to year 8) for three apple cultivars.

Rootstock ^y	Cumulative yield/tree (kg) to year 8 ^z		
	Golden Delicious	Granny Smith	Delicious
M.27 EMLA	47.6 (17)	26.2 (17)	15.3 (17)
P.16	68.7 (15)	56.2 (14)	22.8 (16)
Mark	73.2 (14)	76.6 (12)	27.1 (15)
V.3	108.4 (10)	42.8 (15)	43.9 (11)
MAC.9	68.0 (16)	92.5 (6)	29.3 (14)
P.22	85.7	62.9	--
B.146	--	62.6	38.8
M.9	93.7 (11)	82.6 (10)	34.7 (12)
CG.10	87.5 (13)	72.4 (13)	31.3 (13)
P.2	117.6	64.0	--
M.9 EMLA	117.2 (6)	101.2 (3)	56.4 (10)
V.1	116.0 (7)	100.7 (4)	59.0 (9)
B.9	156.9 (2)	105.3 (2)	82.6 (6)
O.3	128.3	--	76.8
MAC.39	115.9 (8)	80.7 (11)	91.7 (3)
M.26 EMLA	137.2 (4)	95.2 (5)	90.1 (4)
V.7	160.1	126.7	--
C6	110.4 (9)	88.9 (8)	62.1 (7)
V.2	146.5 (3)	122.9 (1)	93.5 (2)
M.7A	122.0	--	82.7
OAR.1	89.5 (12)	40.8 (16)	61.9 (8)
V.4	160.6 (1)	91.4 (7)	100.4 (1)
P.1	123.4 (5)	86.2 (9)	84.0 (5)
LSD P = .05	23.6	22.4	24.5
Cultivar mean ^x	107.1	80.2	58.0

^zRanks are included in brackets for 17 rootstocks common to all cultivars.

^yRootstocks listed in order of increasing tree size (TCA).

^xMeans of 17 rootstocks common to all 3 cultivars.

stock trials have been conducted with a wide range of scion cultivars and the ranking of rootstocks for tree vigor generally has been similar.

TCA at the time of planting and in the early years of the trial was correlated with TCA at the end of year 8 (Table 5). At planting time, 46, 43 and 23 percent of variation (coefficients of determination) in year 8 TCA could be accounted for by variation in TCA at planting time with GD, GS and RD, respectively. Rootstocks with small TCA when dug from the nursery were among the rootstocks with small year 8 TCA. After trees had been in the orchard for three years, over 90 percent of the variation in year 8 TCA was accounted for with each cultivar. Therefore, the final ranking of rootstocks for TCA can be accurately determined as early as the end of year 3.

Van Oosten (31) and Wertheim et al. (35) reported that rootstock differences in TCA were apparent in the nursery and that the relative differences carried forward into the orchard. When preparing trees in the nursery for rootstock trials, it is difficult to achieve uniform tree size for all rootstocks. However, in spite of initial tree size differences, rootstocks assume their final relative tree size by approximately year 3. As noted above, only Mark and MAC.9 failed to retain their ranking as the trees aged, and this appears to be related to the unique soil-line swelling condition with these rootstocks.

Table 9. Coefficients of determination (%) with three apple cultivars for relationships in the early years (3 through 7) versus in year 8 for cumulative yield/tree and cumulative yield efficiency.

Cultivar	No. of rootstocks	Coefficients of determination (%) in year 8 vs years:				
		3	4	5	6	7
Cumulative yield per tree						
Golden Delicious	22	64	82	82	87	94
Granny Smith	21	55	79	91	92	98
Delicious	21	18	91	85	94	98
Cumulative yield efficiency						
Golden Delicious	22	28	81	68	91	93
Granny Smith	21	72	79	89	93	97
Delicious	20	55	62	64	67	84

Table 10. The influence of rootstock on biennial bearing index through 6 cropping seasons (1988-1993) with three cultivars.

Rootstock ^y	Biennial bearing index (x 100) ^z		
	Golden Delicious	Granny Smith	Delicious
M.27 EMLA	42 (5)	32 (4)	57 (7)
P.16	45 (8)	33 (6)	66 (13)
Mark	36 (3)	28 (2)	75 (15)
V.3	35 (2)	44 (11)	61 (10)
MAC.9	33 (1)	26 (1)	75 (16)
P.22	36	25	--
B.146	--	--	51
M.9	41 (4)	31 (3)	58 (8)
CG.10	57 (11)	47 (13)	56 (6)
P.2	43	44	--
M.9 EMLA	49 (10)	35 (8)	59 (9)
V.1	45 (7)	32 (5)	67 (14)
B.9	32	--	47
O.3	56	--	48
MAC.39	61 (13)	45 (12)	66 (12)
M.26 EMLA	48 (9)	34 (7)	45 (1)
V.7	62	36	--
C6	59 (12)	53 (16)	45 (3)
V.2	63 (15)	41 (10)	49 (4)
M.7A	54	--	38
OAR.1	62 (14)	52 (14)	45 (2)
V.4	42 (6)	36 (9)	61 (11)
P.1	70 (16)	53 (15)	55 (5)
LSD P = .05	17	11	22
Cultivar mean ^x	49	39	59

^zThe larger the biennial bearing index, the greater the tendency toward biennial bearing. Ranks are included in brackets for 16 rootstocks common to all scion cultivars.

^yRootstocks listed in order of increasing tree size (TCA).

^xMeans of 16 rootstocks common to all 3 cultivars.

Precocity. Based on the sum of within-cultivar ranks, the number of blossom clusters/tree in year 2 was highest for B.9, O.3 and V.7, followed closely by V.1, M.9 EMLA, M.9, P.22, MAC.9, C6 and M.27 EMLA (Table 6). Four of the most vigorous rootstocks, M.7A, OAR.1, V.4 and P.1, along with CG.10, P.16, M.26 EMLA, B.146 and MAC.39 had the fewest blossom clusters/tree in year 2. With each cultivar the correlation of number of clusters per tree with rootstock vigor (TCA) was low. Correlations among cultivars were also low. For example, M.26 EMLA and P.1 had much higher

blossom cluster counts with GS than with GD and RD and with M.9 EMLA GS had much lower cluster numbers than with GD and RD.

Yield efficiency in year 3 is also an estimate of precocity (Table 7). Based on the sum of within-cultivar ranks, the highest yield efficiency in year 3 occurred with M.9 EMLA, V.7, Mark, V.1, MAC.9, P.16, M.9, P.2 and O.3. The least precocious rootstocks with the lowest yield efficiency in year 3 were OAR.1, P.1, M.7A, V.4, B.146, CG.10 and M.26 EMLA. The extent of early bloom and early yield reported here confirms the precocity of B.9, C6, P.22, P.16 and P.2 and the lack of precocity of M.7 (22).

Yield/tree. The highest cumulative yield/tree at year 8 occurred with the semi-dwarfing rootstocks V.7, V.2 and V.4 and with the dwarfing rootstocks B.9 and M.26 EMLA (Table 8). The least productive trees were with the very dwarfing rootstocks M.27 EMLA, P.16, Mark, P.22 and CG.10. Correlations among cultivars ranged from $r = .469$ ($n = 20$) for the GD/GS relationship in year 4 to $r = .909$ ($n = 19$) for the GD/RD relationship in year 8 (Table 4). Correlations among cultivars were generally lower for cumulative yield/tree than for TCA.

With GD and RD, the ranking of rootstocks for cumulative yield/tree was similar. With the most dwarfing rootstocks (M.27 EMLA, P.16, Mark and V.3), GD was approximately three times more productive per tree than RD but with the most vigorous rootstocks (M.7A, OAR.1, V.4 and P.1) was only 1.5 times more productive than RD. This suggests that in comparison with GD, the weak-growing spur type RD is relatively more productive with semi-dwarfing and semi-vigorous rootstocks than with very dwarfing rootstocks. The reduction in relative productivity of GD on the most vigorous rootstocks may be due in part to the somewhat more severe pruning on these rootstocks. On the other hand, in

Table 11. Mean fruit weight (M.9 EMLA = 100) for 23 rootstocks during 6 seasons with three apple cultivars.

Rootstock	Adjusted mean fruit weight (M.9 EMLA = 100) ²																	
	Golden Delicious						Granny Smith						Delicious					Grand mean ³
	1988	1989	1990	1991	1992	1993	1988	1989	1990	1991	1992	1993	1988	1989	1990	1992	1993	
B.9	98	92	107	104	105	97	--	94	109	92	104	98	109	91	105	114	105	102a
M.9 EMLA	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100ab
O.3	94	94	89	114	103	100	--	--	--	--	--	--	96	90	91	107	102	98a-c
M.26 EMLA	98	93	87	106	105	101	97	94	103	92	99	100	93	92	103	107	97	98a-c
V.7	103	93	89	103	110	104	102	87*	100	94	99	90*	--	--	--	--	98a-d	
P.22	89*	91	89	96	97	88*	114	91	111	97	103	97	--	--	--	--	97a-e	
V.1	88*	94	100	106	107	96	94	90	100	89	98	96	97	100	88	103	100	97a-e
P.2	96	100	101	100	94	88*	107	89	104	85*	100	96	98	103	89	--	99	97a-e
V.3	91	94	96	105	95	93	104	90	96	85*	94	99	102	96	99	102	103	97a-e
MAC.39	101	97	94	97	108	96	95	85*	95	89	103	93	104	89	86	107	99	98b-f
M.9	93	92	92	106	101	87*	95	95	103	94	104	99	93	89	89	98	104	98b-f
C6	89	95	83*	115	103	98	95	87*	99	93	93	89*	90	91	82*	103	99	94c-f
P.16	104	89*	83*	88	89*	83*	111	97	102	97	101	104	86	92	89	--	91*	94c-f
CG.10	97	89*	89	108	95	86*	104	92	107	92	92	93	93	86*	84*	86*	97	94c-g
V.4	103	93	85	96	116	105	81*	77*	95	84*	93	84*	103	84*	98	--	92*	93d-h
M.7A	96	90*	79*	100	110	95	--	--	--	--	--	--	92	91	81*	--	90*	92e-h
V.2	90	92	90	108	106	88*	88	78*	90*	85*	94	90*	89	92	88	100	102	92e-h
B.146	94	93	84	93	--	--	--	84*	86*	81*	94	96	95	95	89	97	102	92f-i
Mark	85*	89*	77*	89	85*	85*	100	93	93	91	95	95	84	82*	85*	92	95	89g-i
M.27 EMLA	92	92	88	97	88*	80*	93	81*	103	88*	88*	83*	87	80*	77*	97	95	89g-i
MAC.9	85*	90*	79*	89	84*	85*	94	96	99	89	91*	98	85	91	81*	76*	96	89h-i
P.1	91	88*	82*	90	110	101	74*	77*	81*	77*	87*	76*	97	82*	77*	97	91*	87i
OAR.1	80*	71*	60*	81	92	88*	--	64*	77*	69*	82*	74*	81	61*	64*	80*	80*	75j
M.9 EMLA mean fruit weight (g)	181	210	248	201	173	181	243	259	299	253	205	229	291	305	300	233	242	--
CV (%)	13	11	19	22	10	10	17	13	10	13	9	9	21	15	19	11	8	7

²Least-squares means adjusted for crop load and presented relative to M.9 EMLA (= 100). Asterisks (*) within columns indicate means are significantly lower than for M.9 EMLA (LSD, P = .05).

³Grand mean separation based on ANOVA with 10 to 17 adjusted means (as % of M.9 EMLA) per rootstock. Means followed by the same letter are not significantly different (LSD, P = .05).

commercial situations more vigorous trees are routinely pruned more severely than less vigorous trees to ensure sunlight penetration into the center of trees.

Of the variation at year 8 in cumulative yield/tree, 64, 55 and 18 percent (coefficients of determination) could be accounted for by first-year production (year 3) for GD, GS and RD, respectively (Table 9). Cumulative yield/tree to year 5 accounted for over 82 percent of the variability in year 8 cumulative yield/tree. In general, yearly yield/tree increased up to years 5 or 6 but showed little increase thereafter. It appears that relative

yield/tree for rootstocks can be accurately assessed by years 5 or 6 or after three or four cropping seasons.

Yield efficiency. Cumulative yield efficiency at year 8 was highest for V.3, P.16, B.9, P.22, M.9, MAC.9, B.146, M.9 EMLA, P.2, Mark, O.3 and V.1 (Table 7). Low cumulative yield efficiency occurred with the most vigorous rootstocks, OAR.1, P.1, V.4, M.7A and C6.

Correlations among cultivars for cumulative yield efficiency ranged from r = .439 (n = 20, not significant) for the GD/RD relationship in year 6 to r = .863 (n = 20) for the GD/GS relationship in year 8 (Table 4). Correlations

among cultivars were generally lower for cumulative yield efficiency than for TCA.

Of the variation at year 8 in cumulative yield efficiency, 28, 72 and 55 percent (coefficients of determination) could be accounted for by yield efficiency in the first year of production (year 3) for GD, GS and RD, respectively (Table 9). Over 90 percent of the year 8 variation in cumulative yield efficiency was accounted for by year 6 yield efficiency with GD and GS but just 67 percent with RD. It does not appear that yield efficiency can be assessed accurately until trees are approximately 7 years of age and have had 5 cropping seasons.

The relationship between cumulative yield efficiency to year 8 and TCA was negative and generally linear with each cultivar. When the data of Autio (3) and NC-140 (22) are plotted for 16 rootstocks with Starkspur Supreme Delicious, similar negative linear relationships are seen. However, in the present study several rootstocks were less yield efficient than other rootstocks in their vigor range, e.g., M.27 EMLA, CG.10 and OAR.1. Others have reported relatively low yield efficiency compared with rootstocks in the same vigor category for M.27 EMLA (4, 11, 35), for P.22 (3), for MAC.39 (3, 22) and OAR.1 (4, 23).

Biennial bearing index. With each cultivar the tendency toward biennial bearing was influenced by rootstock (Table 10). For GD and GS the ranking of rootstocks for biennial bearing index was generally similar ($r = .656$, $n = 19$). The dwarfing rootstocks B.9, MAC.9, V.3, P.22 and Mark had little year-to-year fluctuation in yield/tree and relatively low biennial bearing indices while the more vigorous rootstocks P.1, OAR.1 and V.7 had extreme year-to-year fluctuations in yield/tree and relatively high biennial bearing indices. With RD the ranking of rootstocks for biennial bearing was not similar to the ranking with GD and GS. With RD

the rootstocks with lowest biennial bearing index were M.7A, M.26 EMLA and OAR.1, all relatively vigorous, while the rootstocks with the highest biennial bearing index were MAC.9, Mark, V.1 and P.16, all dwarfing rootstocks.

Average biennial bearing index was not influenced by 6 rootstock and interstem combinations during 7 seasons with Golden Delicious (16). Rootstock influenced biennial bearing index with Starkspur Supreme Delicious but the effect was not related to rootstock vigor (14). From the data of Autio (3) for Starkspur Supreme Delicious, weak rootstocks (P.22, B.9, P.2 and P.16) had a greater tendency to alternate bear than more vigorous rootstocks (P.1, seedling, M.4, M.7 EMLA and P.18). In the present study, also with spur-type Delicious, the highest incidence of biennial bearing also occurred with the weakest rootstocks. If annual bearing requires adequate development of shoot and bourse leaves to supply carbohydrates for flower bud development and fruit set, then spur-type Delicious on dwarfing rootstocks with very limited shoot leaf development may be predisposed to biennial bearing. On the other hand, GD and GS on dwarf rootstocks produced greater shoot and bourse shoot growth than RD and were less biennial.

Fruit weight. Mean fruit weight, adjusted for crop load, was large and similar to the fruit weight of M.9 EMLA for the following rootstocks: B.9, O.3, M.26 EMLA, V.7, P.22, V.1, P.2, V.3, MAC.39 and M.9 (Table 11). Rootstocks with the lowest mean fruit weight were OAR.1, P.1, MAC.9, M.27 EMLA and Mark.

It has been widely reported and observed here that virus-free clones of M.9 and M.26 produce relatively large fruit (2, 3, 23, 32, 35). The present study confirms low mean fruit weight reported for OAR.1 (2, 23), P.1 (35), Mark/MAC.9 (23) and M.27 (2, 23, 27, 32, 35, 36). In three of the above

studies (2, 3, 35) fruit weight was adjusted for variation in crop load.

Several dwarfing rootstocks performed well in this trial and are worthy of commercial recommendation while other rootstocks appear to have sufficient promise to be planted in small scale commercial trials. Virus-free M.9, the worldwide standard dwarfing rootstock, has been outstanding for precocity, yield efficiency and fruit size in this trial. B.9, in the M.9 EMLA vigor range, has been similar in most respects to M.9 EMLA but has the advantage of greater winter hardiness. O.3, between M.9 EMLA and M.26 EMLA in tree vigor and slightly more vigorous than B.9, has been productive, has had large fruit size and also has winter hardiness. Both B.9 and O.3, because of these qualities and extensive testing over many years and at numerous sites (22, 23, 24), can be recommended for commercial use. O.3 has been somewhat difficult to propagate (29). The following dwarfing rootstocks, based on their performance in this trial, are promising and worthy of trial by orchardists: V.3 and P.22, both less vigorous than M.9 EMLA; P.2 and V.1 in the M.9 EMLA vigor range; and V.2 and V.7, in the M.26 EMLA to M.7A vigor range. A weakness of B.9, O.3, P.22 and P.2 is their susceptibility to fire blight (9). The reaction of the Vineland series to fire blight is not known. However, until a new series of fire blight-resistant rootstocks (10) has been widely tested and can be recommended, the rootstocks listed above are worthy candidates in their respective vigor ranges for commercial use.

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