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BARD

FINAL REPORT

PROJECT NO. IS-3284-01

**Influence of Hydraulic Properties of Rootstocks and
the Rootstock-Scion Graft on Water Use and
Productivity of Apple Trees**

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2003

6589 70
BARD Final Scientific Report
Cover Page

Date of Submission of the report: August, 2003

BARD Project Number: IS3284-01

Project Title: Influence of hydraulic properties of rootstocks and the rootstock-scion graft on water use and productivity of apple trees

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Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.

Abbreviations commonly used in the report, in alphabetical order:

Budget: IS: \$ 47000

US: \$ 53000

Total: \$ 100,000

מינהל המחקר החקלאי
מרכז וולקני
ספרייה מרכזית

2004-נב-10

נתקבל

Signature
Principal Investigator

Signature
Authorizing Official, Principal Institution

63-12
BAP-INT

Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted)	1		1	2
Submitted, in review, in preparation				
Invited review papers				
Book chapters				
Books				
Master theses				
Ph.D. theses				
Abstracts	1			1
Not refereed (proceedings, reports, etc.)				

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings		1	1	2
Longer Visits (Sabbaticals)		1		1

Description of Cooperation:

Cooperation between the Israel team consisted of joint experiments during the summers of 2001 and 2002, followed by analysis of results. Cooperation between the PI and Co-PI was by email, and in the year long visit of the PI in the Co-PI's lab during a sabbatical year from August 2001 to July 2002. Cooperation with the Cornell group was by email discussion. Lakso, Robinson and Naor all visited the PI and Co-PI in Burlington. The Cornell group provided plant material to the Burlington lab, and was in charge of the NC-140 trials at the University of Vermont facility where the US field work was carried out.

Patent Summary (numbers)

	Israeli inventor (s) only	US inventor (s) only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)				
Licensed				

Bard Project No. IS-3284-01

Project Title: Influence of hydraulic properties of rootstocks and the rootstock-scion graft on water use and productivity of apple trees

Abstract (1 page single space):

This one year exploratory project investigated hydraulic architecture of apple dwarfing rootstocks. The hypothesis was that hydraulic conductance is correlated with rootstock vigor. A previous study of trees on three rootstocks in Israel showed that dwarfed trees used less water than un-dwarfed trees. Analysis showed that if the tree maintains leaf water potentials above minimum values, then this implies that the dwarfed trees have lower leaf conductance, which may also be the cause of dwarfing. The current project studied small 2-year old unworked rootstock trees, and full sized trees bearing commercial yields. In both cases hydraulic conductance was determined with two methods – the non-destructive evaporative flux (EF)-leaf water potential (LWP) method, and a destructive method in which water was forced through the plant at known pressure using the “high pressure flow meter” (HPFM). Detailed work allowed measurement of conductance of the rootstock-scion union. This was achieved both with the HPFM and with the EF-LWP methods, the former in the US and the latter in Israel. Direct measurements of leaf conductance were made, and carbon isotope ratios ($\delta^{13}\text{C}$) were determined for leaves sampled at the end of the season. The latter can indicate sustained differences in leaf conductance behavior.

HPFM and EF-LWP methods did not give the same results. In the small plants results were similar in magnitude, but not significantly correlated. In large trees, EF-LWP measurements were a fraction of those obtained with the HPFM. The latter indicates that some of the xylem is not normally functional but transports water when pressurized. Additional experimental work targeted this result. Xylem was stained before and after perfusion with water at high pressure. This showed that at least for one rootstock a significant amount of xylem was blocked before perfusion. The “air method” for determining xylem vessel properties was improved and employed. Length, radius and density of xylem vessels of different rootstocks were found to be similar, and significant differences found were not clearly related to rootstock vigor.

Measurements in the commercial orchard in Israel showed that the graft union in a dwarfing rootstock was a large obstacle for water transport (i.e. had a high resistance). This apparently led to low leaf conductance to water vapor, as indicated by lower $\delta^{13}\text{C}$, which implies low internal CO_2 concentrations.

In the US orchard, $\delta^{13}\text{C}$ in 2001 was correlated with rootstock vigor, and significant differences were found in leaf conductance. However, the $\delta^{13}\text{C}$ differences were not observed in 2002, were opposite to those found in the Israeli orchard, and measurements of the graft union with the HPFM did not find large resistances. We speculate that the graft union is not necessarily a large impediment to water transport unless the scion starts to separate from the rootstock.

It was concluded that significant differences in hydraulic conductance exist between different dwarfing rootstocks. These differences may be caused by differences in xylem properties and in the degree of cavitation, as well as resistance in the graft union. However, no general relationship to rootstock vigor was found. Therefore, hydraulic conductance alone cannot explain dwarfing, but may be one of two or more factors that lead to dwarfing. Future work should integrate more factors with hydraulic relations, e.g. nutrient and solute transport and production of hormones.

Achievements (up to 3 pages space 1.5):

Theoretical analysis of the relationship between sap flow and leaf water potential, together with the linear relationship between canopy resistance to vapor transport and sap flow, led to a direct relationship between hydraulic conductance to water transport and canopy resistance. Application of the model to old results showed that the slope of the relationships between mid-day R_c and D for the 1998 data from three rootstocks could be predicted using common values of specific hydraulic conductance, k_s ($0.134 \text{ kg m}^{-2} \text{ s}^{-1} \text{ MPa}^{-1}$) and mid-day leaf water potential Ψ_l (-1.34 MPa) for the three rootstocks. This means that for this case, the difference in canopy conductance between the rootstocks could be predicted based on the differences in stem cross section.

A mathematical technique was developed for determining vessel length distributions from air method measurements of xylem conductivity to air (Cohen et al., submitted). This included derivation of a new vessel length distribution function.

Infiltration of stem segments of unworked rootstocks with basic fuchsin stain demonstrated that in some cases there is significant xylem dysfunction in the stems. Some of the uncondutive area of the stems became conductive after perfusion with water at high pressure. Further work should be lead to measurements of the percent loss of xylem conductivity in the different rootstocks.

Hydraulic conductance of 9 unworked and 6 grafted rootstocks was measured. Although no clear relationships with vigor were found, this is a large set of measurements and analysis of the results is not yet complete. Conductance of the graft union was made on two rootstocks in Israel (12 trees) with the EF-LWP method. Conductance of the union was much lower in the dwarfing rootstock M9. Results for M9 in Vermont, measured with the HPFM, did not show such large reductions in conductance at the union. We speculate that in the Israeli orchard the scion tissue is beginning to separate from the rootstock.

Agricultural and/or economic impact of the findings:

The economic importance of dwarfing rootstocks is extensive. Currently it takes many years to determine the vigor class of a rootstock. The main objective was to see if hydraulic characteristics of unworked rootstock plants and/or those of fully grown grafted trees, are correlated with vigor class. This would then open the way for

developing 'diagnostic' tools that could give early indications of rootstock vigor. Unfortunately, we found that the situation is more complicated than we thought. Although some hydraulic parameters differed significantly in the different rootstocks, none of the relationships between the hydraulic parameters and rootstock vigor were unambiguous, ie. there was no monotonous relationship between any of the parameters and rootstock vigor.

The carbon isotope ratio of leaves in the orchard at the top of the canopy sampled at the end of the season in 2001 did increase monotonously with increasing rootstock vigor, implying higher internal CO₂ in leaves on the dwarfs. This was not observed in 2002. The difference is probably due to the climate when the leaves grew, which caused differences in leaf conductance behavior. We speculate that when the late spring is dry, as occurred in 2001, these differences will be observed.

In the analysis of the old results (Cohen and Naor, 2002), we found that specific hydraulic conductance between the rootstocks was similar. This implies that differences in water use between the three rootstocks were proportional to the stem cross sections, and indicates that for irrigation scheduling stem cross section may be an important parameter.

In summary, since the main hypothesis, that hydraulic conductance is related to rootstock vigor, was not proven, hydraulic conductance can not yet be used as a 'diagnostic' parameter for characterizing rootstock vigor, although it may be useful in the future as one of a number of parameters. The development of theory and methods for measuring vessel length distributions in plants may have wider importance that might lead to research with economic implications, eg. determination of cut flower vessel lengths.

Details of cooperation:

The PI spent a sabbatical year (August 2001-July 2002) in the co-PI's lab in Burlington VT. There, he collaborated with the co-PI on a series of experiments with the small apple trees in the lab and in the field on the 10 year old trees in the University of Vermont's (UVM) Horticultural Research Center in Burlington. The experiments involved using some new equipment (the HPFM and other pressurized systems), and other techniques previously unknown to the PI. By the end of the year the PI was skilled with the use of the HPFM and had used several other techniques for examining xylem properties and dysfunction (see paper Cohen et al., 2003). In

addition, the PI brought sap flow sensors developed in Israel, and familiarized the co-PI with their use. After returning to Israel, the PI and his technician built their own HPFM, which is currently being used for examining hydraulic properties of other grafted plants.

The US Cornell collaborators visited the Burlington lab to observe and discuss the experiments. They provided most of the small trees, and granted us access to the UVM's orchard, which was a rootstock trial managed by their institution. The last collaborator (Naor) visited the Burlington lab during the year. He ran the parallel field experiments in Israel during the summers of 2001 and 2002 during the PI sabbatical.

Finally, the PI plans to attend a conference in the US in September, 2003, (Irrigation of Horticultural Crops, ISHS, Davis, CA, Sept 1-5, 2003) where he will present some of the project's results, and will meet with the US Co-PI (Tyree) and the other investigators (Lakso and Naor) to discuss mechanisms of rootstock dwarfing and how this research can be continued.

List of publications:

Cohen, S. and A. Naor (2002). The effect of three rootstocks on water use, canopy conductance and hydraulic parameters of apple trees; and predicting canopy from hydraulic conductance. *Plant Cell and Environment* 25(1):17-28.

Cohen, S., Bennink, J. and M. Tyree (2003). Air method measurements of apple vessel length distributions with improved apparatus and theory. *Journal of Experimental Botany* 54(389):1889-1897.

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Appendix 1. Hydraulic conductance of the graft union measured in the Golan Heights

S. Cohen and A. Naor

Introduction:

It was hypothesized that the resistance of the graft union to water transport is larger in dwarfing rootstocks than in more vigorous rootstocks. This experiment determined hydraulic conductance from measurements of leaf water potential and tree sap flow. Hydraulic conductance was partitioned into two components: from soil to root, and from root to scion stem. The latter includes the graft union.

Methods:

The measurements were performed in August 2002 in commercial apple orchards in the Golan Heights. The trees were of the Golden Delicious variety on two rootstocks, MM106 (semi-vigorous), and M9 (dwarf). All trees had suckers growing from below the graft union, and care was taken not to prune these during the season, as usually done in standard orchard maintenance. Sap flow sensors (Cohen et al., 1981) were installed in eight trees from each rootstock during July, several weeks before the intensive measurements. Irrigation was excessive, guaranteed by adding additional drippers for each of the trees. Sap flow was monitored continuously and on August 8, 2002 leaf water potentials before dawn and during mid-day hours were measured using the pressure chamber technique. During mid-day covered leaves (covered several hours before) were measured from the tree and suckers (Naor, 1998). Leaves on the suckers were all shaded with highly reflective 70% Aluminet shade screen as an additional impediment to evaporative losses. In a prior similar experiment in Sept, 2000 pre-dawn measurements were not performed, but sunlit and shaded leaves were also measured. The latter results are not included in this report.

Pre-dawn leaf water potential was taken as representative of soil water potential, and covered leaves were assumed to be in equilibrium with that of the wood xylem to which they were attached, so covered leaves from suckers represent root water potential below the graft union, and covered leaves from the scion represent the scion stem. The basic equation for hydraulic conductance (k) is:

$$k = \frac{F}{\Psi_a - \Psi_b}$$

where Ψ represents water potential, F flux in the stem, and a and b represent places where water potential was measured. So from the measurements made we partitioned between conductance from soil to root, from root to scion stem (including the graft union), and from scion stem to sunlit and shaded leaves. Leaf area was measured in the fall. All leaves were harvested and for some trees all area was measured in a Delta-T leaf area machine. For a few, fresh weight to area ratios were determined for three sub-samples and total area was determined from total fresh weight.

Results:

Here we present results from 2002, since the data set for 2000 is incomplete and the main findings are clearer in the 2002 experiment. Figure 1 shows mid-day water potentials for soil, stem, and root determined in August 2002. The difference between the two

Fig 1. Mid-day water potential in trees measured in 2002. For details see text.

rootstocks is only in the root water potential (RWP), determined from the covered sucker leaves. In MM106 RWP is close to that of the stem, because of the good hydraulic contact between roots and scion (i.e. the graft union), while for M9 the resistance is much larger, so that RWP is intermediate between that of the root and stem. The similarity in stem water potential is in agreement with the hypothesis that the plant maintains a constant minimum water potential through modulation of leaf conductance.

Figure 2 shows leaf specific resistance (i.e. $1/k$) of the different components of the plant. The resistance of the graft union is in the component from root to stem. The latter resistance of M9 is significantly (several times) higher than that of MM106.

Fig 2. Leaf specific hydraulic resistance of components of the two rootstocks in 2002

However, total resistance, from soil to stem, was not significantly different in the two rootstocks, since the main resistance in trees is in the root system and in the transition from soil to roots (e.g. Tyree, 1999).

Table 1 shows several parameters of the experiment. In particular it is clear that the ratio of sap flow between the two rootstocks is disproportionate to the differences in tree size. This demonstrates that the leaf conductance to water vapor transport must have been lower in M9. Further evidence for this difference can be found in the δC^{13} measurements (Fig 3). δC^{13} is negatively related to

the internal CO_2 concentration in the leaves when their carbon was fixed. In this case the lower values in MM106 indicate higher internal CO_2 , which is characteristic of generally higher leaf conductance.

Fig 3. Carbon isotope ratios $\delta^{13}C$ measured in scion leaf samples from the upper canopy of trees measured in 2002

Table 1. Parameters of the trees measured in 2002 at Ein Zivan in the Golan Heights.

Ein Zivan, 2002			
	M9	MM106	M9/MM106
Planting Distance	4x1.2	4x1.5	
Planting m2/tree	4.8	6	0.80
LA/tree m2	5.3	7.4	0.72
Stem Diameter, cm	5.0	6.6	0.76
Midday Sap Flow per tree l/h	0.6	1.3	0.49
Stem Area/tree m2	2.0E-03	3.4E-03	0.58
LAI	1.1	1.2	0.91
SapFlow mm/h	0.13	0.21	0.61
Stem Area index	4.2E-04	5.7E-04	0.73
Stem area/leaf area	3.8E-04	4.7E-04	0.81

Appendix 2. Hydraulic conductance of two year old unworked rootstocks of a range of vigors

S. Cohen, J. Bennink and M. Tyree

Introduction:

It was hypothesized that if hydraulic conductance is influential in dwarfing then hydraulic conductance of unworked rootstocks would give an indication of the rootstock vigor.

Methods:

Two groups of rootstock plants were obtained. The first set consisted of two year old plants propagated from stoolbeds in standard nurseries. These were delivered to the Burlington lab in May 2001, and maintained in the heated greenhouse in a long photoperiod to prevent dormancy until they were measured. Upon arrival plants were replanted in a sandy soil mix to enable root extraction after the measurements. This group included the following rootstocks: MM111(8), MM106(7), M26(4), M9(3) Geneva16(3) and G16L10(3) (a derivative of Geneva16). Vigor class is given in parentheses next to each rootstock name. The second set of rootstocks, which were seed propagated was obtained in fall 2001 from the Elmore Roots Organic Nursery in Elmore VT. These were transferred to the greenhouse in a dormant state and leafed out before measurement. Seedling rootstocks are considered to be in vigor class 10.

Two methods were used to measure hydraulic conductance. For the EF (evaporative flux) method plants were well watered, pre-dawn leaf water potential was measured and then the pot was bagged to prevent evaporation from the soil. Water loss was determined by hourly weighing with a precision balance between 1000 and 1400 hours. In between hourly weighing (on the half hour) leaf water potential was measured on covered leaves. As in the field experiments, pre-dawn LWP was taken as soil water potential and covered leaves were taken as stem water potential. Data were used to determine hydraulic conductance from soil to stem. On the following day, hydraulic conductance of the root system was measured with the "high pressure flow meter" (HPFM; Tyree et al., 1995; Tsuda and Tyree, 2000). For this procedure, the stem was cut about 10 cm above the soil, then recut with a fresh razor blade, and fitted with the high pressure fitting. Three initial transient measurements of hydraulic conductance were made, followed by perfusion for

approximately 30 minutes, when a quasi-steady state reading was taken, and followed by more transient measurements.

After completing the series of measurements leaf area was measured in a Licor leaf area machine (including leaves removed for measurements of leaf water potential). Roots were extracted by washing away the sandy soil mix. Several root samples were stained and their surface area determined from scanned images made on an HP Scanjet scanner, using Delta-T Scan software. The root samples were then oven dried and the ratio of dry weight to surface area determined. Total root surface area was determined using the average ratio of the root samples and the total root dry weight.

During part of the experimental period greenhouse climate was monitored. Photosynthetic radiation was measured with a Quantum sensor (Licor LI190), wind speed with a hot wire anemometer, and temperature and relative humidity with wet and dry thermocouples enclosed in an aspirated box. Mean leaf conductance was estimated assuming equivalence between leaf and air temperatures by:

$$G_l = \frac{F}{VPD}$$

where G_l is leaf conductance (m s^{-1}), F is sap flux on a leaf area basis ($\text{g m}^{-2}\text{s}^{-1}$), and VPD is the air absolute humidity deficit (g m^{-3}).

Results:

Differences were found in development of the different rootstocks. Fig 1 shows mean leaf, root and stem cross sectional area for the plants measured during the experiment. Since the measurements were made during a nine month period (September 2001 to May 2002) some of the differences are due to the time of sampling. But many of the differences were not, e.g. EMLA111's were sampled at the same time or earlier than most of the others including EMLA106, yet they had the same or more leaf and stem area. EMLA26 in particular did not develop well in our conditions, and although most of these plants died, a few were available for measurements. Leaf area varied most between plants, from 0.1 to 0.6 m^2 per plant, and similar variation was found in root surface area, 0.2 to 1 m^2 . Leaf area (LA) and root area (RA) were significantly correlated, with $RA=1.17 LA$, $r^2=0.29$ ($p<0.01$). Stem cross sectional area, in contrast, was relatively stable, varying from 1.1 to 1.7 $\times 10^{-4} \text{ m}^2$. The ratios between leaf area and stem area (ie. The Huber value) varied from

2e-4 to 4.5 e-4 for 7 of the rootstocks, while for EMLA26 it was very high, $\sim 10e-4$, due to low leaf area. Root area was weakly related to stem area ($r^2=0.13$; $p<0.05$) but leaf area was not.

EF-LWP measurements of hydraulic conductance showed that there were significant differences between rootstocks (fig 2), especially when normalized by root surface area (Kr). The highest conductance was found in EMLA111, the strongest rootstock, and Kr was significantly higher in EMLA111 than in the dwarfing rootstocks (M9, Bud9, G16L10, and Geneva16). However, EMLA106, which is a semi-dwarf, was not significantly different from the dwarfs, and the seedling plants (prunifolia and antanovka) had low hydraulic conductance.

Fig 3. shows the significant relationship found between hydraulic conductance, as measured by the EF-LWP method, and root surface area. The ratios of root surface area to stem cross section and leaf area (fig 4) were significantly different in some of the varieties, but there was not clear connection between rootstock dwarfing potential and these parameters.

Fig 5. shows high pressure flow meter (HPFM) measurements of root specific hydraulic conductance measured on the rootstock plants. The measurements are of the lower portion of the stem and the root system. The path measured, ie. From root through the stem, is similar to the path measured by the EF-LWP method, which considered pre-dawn leaf water potential to represent that in the roots during the day, and stem water potential as measured in covered leaves. Fig 5 shows results for 4 measurements, two with the transient procedure in which measurements are made while applied pressure is increased gradually, and two quasi-steady state (QSS) measurements in which pressure is constant until steady state flow rates are obtained. Results show that EMLA106, EMLA111, EMLA26 and M9 had higher conductance than Bud9, G16L10, Geneva16 and Prunifolia. This result does not correlate with dwarfing potential, since the first 4 represent strong and weak rootstocks, while the second group includes a seedling plant with three dwarfing rootstocks.

HPFM and EF-LWP measurements were not significantly correlated (fig 6), but results were of similar magnitudes. Since the HPFM forces water through the plant, we expect that if there were any embolisms they would be forced out by the HPFM. Therefore, it would be expected that the HPFM should give higher values than the EF method, and the ratio of the EF to HPFM results should be less than one. Fig 7 shows that this is the case for all except EMLA111. In this analysis the highest

values, which might indicate the lowest amount of cavitation, were for the two strongest rootstocks, EMLA111 and EMLA106.

Figure 1. Leaf area, root area, and stem cross sectional area for the rootstock plants in the greenhouse at the Forest Service lab in Vermont.

Fig 2. results of EF-LWP measurements of hydraulic conductance of two year old unworked rootstock trees. Water loss was measured by weighing. Vertical lines denote standard error of the mean. Units for conductance are $\text{kg s}^{-1} \text{Mpa}^{-1} \text{m}^{-2}$ where K_s , K_l and K_r represent stem (A), leaf (B) and root (C) specific conductance, respectively.

Fig 3. Relationship between plant conductance and root surface area.

Fig 4. Ratios of root surface area to leaf area and stem cross sectional area for the rootstock plants.

Fig 5. High pressure flow meter (HPFM) measurements of root specific hydraulic conductance for the rootstock plants. The vertical bars represent standard error of the mean of the different plants measured. Two transient (Trans) and two quasi-steady state (QSS) measurements were made on each plant.

Fig 6. Relationship between conductance measured by EF-LWP and HPFM methods. The line is the least squares regression fit for the relationship between transient HPFM and EF-LWP methods. Data points are for individual plants. Neither of the relationships was statistically significant.

Fig. 7. Ratio of measurements made by the EF-LWP method to those made with the HPFM. Average transient and quasi-steady state measurements are presented separately. Results are for plants on which both measurements were made.

Appendix 3. Hydraulic conductance of apple trees on rootstocks of a range of vigors

S. Cohen, J. Bennink, and M. Tyree

Introduction:

It was hypothesized that if hydraulic conductance is influential in dwarfing then hydraulic conductance of fully grown trees on rootstocks of different vigors would be correlated with rootstock vigor. In addition, we wanted to know if there were differences in conductance of the rootstock-graft region of the stem. In this experiment most of the measurements were with the EF-LWP method, but a few trees were also harvested and measured with the HPFM method.

Methods

The experiment was done in the University of Vermont's (UVM) horticultural research center in Burlington VT. Trees were from the NC-140 rootstock trial, which was an evaluation of selections for the Cornell/Geneva Rootstock Breeding Program with the Scab-resistant scion cultivar 'Liberty'. Trees were planted in 1992 in three rows, with each row representing one of the types: dwarf, semi-dwarf, and vigorous. The rootstock varieties varied at random in the row. From the rootstock varieties we selected two of each type for the current study: Vigorous M111 and CG934; Semi-dwarf M7A and CG30, and dwarf M9 and CG202.

The orchard was rain-fed, since there is usually ample rain in the summer. However, supplemental irrigation was supplied with drippers. The summer of 2001 had a drought spell, during which the orchard was irrigated, but not regularly, especially when the water in the farm's reservoir became low.

Measurements were made during the summers of 2001 and 2002. A heat pulse type sap flow measurement system, which measures 8 sensor probes simultaneously, was installed in the orchard (Cohen et al., 1981). Four trees of each type (2 per variety, totaling 12 trees) were measured by moving four probes from one row to the next after a few weeks of measurement. On selected days, leaf water potentials were measured with a pressure chamber from pre-dawn through the course of the day, in trees in which sap flow was measured. Water potential was determined for leaves sealed at the end of the previous day in aluminum foil (so these leaves represented stem water potential), and for sunlit and shaded leaves. Data were used to determine hydraulic conductance for the soil to stem and stem to leaf pathways, as done

elsewhere (see appendix 1 and Cohen and Naor, 2002). Climate data was measured with an automatic weather station operated by the UVM staff. On selected days, leaf conductance was measured with a steady state porometer (Licor LI1600, Lincoln NE).

Leaves were sampled for carbon isotope analysis in the fall of both years. Ten leaves from each tree were harvested and stored separately. The leaves were from fully exposed positions on extension shoots near the end of the shoot (between leaf 2 to 8). An equal number of disks was cut from each leaf and these were ground in a Wiley mill and sent to the Weizmann Inst of Science in Rehovot, Israel for analysis.

In the fall of both seasons, all leaves were harvested from the trees. These were weighed and at least three sub-samples from each tree were taken for determination of the ratio of leaf area to fresh weight. The average ratios were then used to determine total leaf area for each tree.

Results:

The most notable influence of the dwarfing classes on growth of the trees is in stem cross sectional area and less in leaf area (fig 1). With respect to stem cross section, this rootstock trial would grade the trees from most vigorous to least as: CG934, MM111, CG30, M7A, CG202 and M9.

Fig 2a shows the relationship between leaf area and stem area for the individual trees, as measured in 2001. The data seem to fall on two distinct lines, with a lower slope for the vigorous rootstocks, CG934 and MM111. Huber values (stem area per leaf area) calculated for these trees, in addition to three values for similar trees measured in Israel (Cohen and Naor, unpublished data), are given in fig 2b. For the individuals in Vermont, the Huber values demonstrate the differences noted above, with the exception of M9, whose low values in fig 2a precluded determining on which line it fell. Including the Israeli data demonstrates that the values from the two locations are very close, but the reduced Huber values for the dwarfing rootstocks observed in the Vermont individuals was not observed in the Israeli case.

Figure 3 presents results of carbon isotope ratios ($\delta^{13}\text{C}$) measured in the fall of both seasons. The leaves sampled developed during the end of the summer. In 2001 a significant trend was observed, with lower values occurring in the weaker rootstocks. Lower values are indicative of higher internal CO_2 concentrations during leaf development. The trend was not observed in 2002. The summer of 2001 was characterized by low rainfall, and during the drought the UVM farm's reservoir was

low, so irrigation was below the level usually given to the orchard and atmospheric evaporative demand was relatively high. Therefore, we speculate that the trend in $\delta^{13}\text{C}$ observed during 2001 was an expression of differences in drought response of the trees.

Fig 4 gives mid-day leaf conductance measured in the summer of 2002 and leaf water potential measured in 2001. In both cases there were significant differences between rootstocks, but there was no general trend related to dwarfing potential.

Similarly, leaf and stem specific hydraulic conductance (fig 5) showed no general trends that can be related to dwarfing potential. The values marked soil-stem stem-leaf and soil-leaf indicate partitioning of the conductance in the water transport pathway. If anything, the vigorous rootstocks may have slightly **lower** hydraulic conductance than the dwarfing ones, which is opposite to the hypothesis of this research.

Measurements of tree hydraulic conductance was also made with the HPFM method. Eight trees were measured, and results were of the same order of magnitude, but generally higher than those obtained with the EF-LWP method. HPFM results were significantly correlated with the EF-LWP results (fig 6). The measurements presented here were made in the quasi-steady-state mode of operation of the HPFM. The order of measurement was as follows: first the tree stem was cut well above the region of union between rootstock and scion. The HPFM was connected to the upper part of the severed tree, and the tree was perfused with water at pressures of approximately 0.6 Mpa for at least half an hour. After taking the steady state reading, the leaves were removed and another reading taken. The HPFM was then connected to the cut stem that was still connected to the root system. The root system was perfused for a half hour and a steady state reading taken. The stem was then severed below and then above the graft union region and readings were taken. Using this series of results we were able to differentiate between the conductance of the different parts of the tree. Fig 6 shows the leaf specific resistance of the tree parts for the different rootstocks. The total resistance is the sum of the resistance for all parts. However, as found with the small rootstock plants, no clear correlation to rootstock vigor was found.

The ratio of the results obtained by the two methods (EF-LWP and HPFM) may be indicative of the extent of cavitation in these trees (fig 7). However, this parameter also did not show a significant correlation with rootstock vigor.

Fig 1. Stem and leaf area for the trees in the NC140 rootstock trial, as measured in 2001.

Fig 2A. Relationship between leaf area and stem cross sectional area for the rootstocks. B. Huber values (stem area/leaf area) for the UVM trees and for three rootstocks in the Golan, Israel.

Fig 3. Carbon isotope discrimination values for apple leaves picked in the fall of 2001 and 2002. Significant differences were found in 2001, and letters indicate groups according to Duncan's multiple range test.

Fig. 4. Sunlit leaf conductance (a), and predawn and mid-day stem water potential measured at the UVM Hort farm.

Fig 4. Leaf specific hydraulic conductance measured by the EF-LWP method for the trees in the UVM Hort farm. Soil to stem, stem to leaf, and soil to leaf pathways are given separately.

Fig 5. Relationship between leaf specific hydraulic conductance of 8 apple trees measured by the EF-LWP method, and the HPFM method.

Fig. 6. Leaf area specific hydraulic resistance of the different parts of the trees in the UVM orchard. Eight trees were measured, and values are for the different rootstocks, where two of the values are averages, and the others for individual trees.

Fig 7. Ratio of hydraulic conductance measured by the EF-LWP method to that measured by the HPFM method. The data are for individual trees in the UVM Horticultural Research center.